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PROPOSED REVISIONS TO MIL-F-8785C RELATED TO FLIGHT SAFETY OF AUGMENTED AIRCRAFT
VOLUME I
SECTION 1 THROUGH 7, REFERENCES

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New tentative criteria have been developed for airplanes with relaxed static longitudinal stability based on approach and landing ground simulation, but augmented by the available flight test data. It is shown that a criterion based on just time-to-double amplitude is invalid, and other elements in the pitch attitude transfer function must be included. Criteria based on both closed-loop frequency response and airplane parameters (open-loop) are developed. This report covers the results obtained in one of a series of Air Force programs to update MIL-F-8785, 'Flying Qualities of Piloted Airplanes.'

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FOREWORD

This report was prepared for the United States Air Force by the Boeing Military Airplane Company, Seattle, Washington, in partial fulfillment of Contract Number F33615-78-C-3603, Project 2403, Flight Control, Task 05, Work Unit 21. The report describes proposed revisions to MIL-F-8785C related to flight safety of highly augmented aircraft, especially those with relaxed static stability. The proposed revisions are based on analysis and fixed base ground simulation.

The contract was under the direction first of Mr. R. Kevin Rowe, then Mr. G. Thomas Black, and finally Mr. David J. Moorhouse, all of the Control Criteria Branch, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio. The support and encouragement provided by David Moorhouse are gratefully acknowledged.

The report represents the combined effort of many people of the Boeing Military Airplane Company, both in Seattle and Wichita. The technical work was under the direction of John M. Schuler, Principal Investigator, and Donald E. West, Program Manager. The accident/incident data analysis was performed by Pete Wylie, assisted by Gary Walker, Ove Moutka, and David Wilson of the Experience Analysis Center.

The proposed revisions to improve compatibility with MIL-F-9490D were developed by Garold Hodges and Olin Visor of the Flight Control Group and Donald Nordwall of the Aerodynamics Group, all of Boeing Wichita. The ground simulations were performed on the Boeing Visual Flight Simulator facility at Kent, Washington, under the trying circumstances imposed by significant off-hours operation, and the personnel of that facility are to be commended for their equanimity and outstanding effort, especially Gene Bird for overall operation and computer programming and Larry Hilliard and Bob Copeland for visual system operation and maintenance. The evaluation pilots, who performed their all important role with professional competence despite the trials of a compressed and irregular off-hours schedule, were Andrew Messer (Pilot A), Ray McPherson (Pilot R), and Terry Kriha (Pilot T).

Recognition is due Robert P. Harper, Rogers E. Smith, Charles R. Chalk, Robert C. Radford and James Lyons of the Flight Research Department of Calspan Corp. for their assistance in obtaining and

checking out the Neal-Smith computer program, and for many hours of telephone consultation in several areas.

Particular recognition for their substantial analytical effort and technical contribution to the project is due Phillip Gotlieb and Dr. Thomas Liang. For her typing, ability to decipher our unreadable (sometimes even to us) hen scratches, and forbearance, the authors thank Jeanne Hunt. Finally, the primary author would like to express his gratitude to Donald E. West, William Kehrer and Richard McCorkle for their encouragement and support, and for providing the resources for the second simulation program which produced the most significant data used in this stuay.

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(1) This is an abbreviated table of contents for all three volumes of this report. Complete table of contents for Volume I follows.

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LIST OF SYMBOLS

$A_{S(fq)}$	flight safety allocation factor for flying qualities
A_θ	high frequency gain in θ/F_s transfer function
A_h	high frequency gain in h/F_s transfer function
c	wing chord, reference chord, ft
C_L	lift coefficient, L/qS
$C_{L\alpha}$	lift curve slope, $\partial C_L/\partial\alpha$
C_m	pitching moment coefficient, M/qSc
C_{m_α}	$\partial C_m/\partial\alpha$
$\bar{c}$	mean aerodynamic chord, ft
D	aerodynamic drag, parallel to flight path, lb
dB	decibels. 20 $\log_{10}$ amplitude
F_s	pitch control force, applied by pilot, lb, pull = +
g	acceleration of gravity, ft/sec^2
h	altitude, ft
$\dot{h}$	rate of change of altitude, rate of climb, ft/sec^2
I_y	moment of inertia about y-axis, slug-ft^2
j	$\sqrt{-1}$
K_p	gain in pilot model
L	aerodynamic lift, normal to flight path, lb
M	Mach number
M	aerodynamic pitch moment about y-axis, ft-lb
m	mass of airplane, slugs
M_c	normalized pitching moment due to pitch control, $M_{control}/I_y$, rad/sec^2
$M_{c_{max}}$	maximum normalized pitching moment due to pitch control, rad/sec^2
M_i	$= \frac{1}{I_y}\frac{\partial M}{\partial i}$, $i = \alpha, u, q, \delta_e, \delta_h, \delta, \dot{\alpha}$
M_{F_s}	$= \frac{\delta_{ES}}{F_s} M_{\delta_{ES}}$, rad/sec^2/lb, deg/sec^2/lb

LIST OF SYMBOLS (continued)

$M_{\delta_{ES}}$	$= \frac{\delta_e}{\delta_{ES}} M_{\delta_e} = \frac{\delta_h}{\delta_{ES}} M_{\delta_h}$, rad/sec^2/in
n	normal acceleration or load factor, g's, up = +
n_z	normal acceleration along z-axis, g's, down = +
q	dynamic pressure, lb/ft^2
q	pitch rate about y-axis, rad/sec, deg/sec
$Q_{S(fq)}$	maximum allowable probability of worse than Level 3 flying qualities (aircraft loss rate), per flight
$\dot{q}$	time rate of change of pitch rate q, rad/sec^2
R_S	overall airplane flight safety requirement, per flight
s	Laplace operator
S	wing area, ft^2
t	time, sec
$T_{1/2}$	time to half amplitude, oscillation or convergence, sec
T_2	time to double amplitude, oscillation or divergence, sec
T_{θ_2}	time constant of larger zero in θ/F_s, sec
T_{θ_1}	time constant of smallest zero in θ/F_s, sec
T_{h_1}	time constant of smallest zero in h/F_s, sec
u	incremental velocity along x-axis, ft/sec
u_g	gust velocity along the x-axis, ft/sec
V	airspeed, ft/sec, knots
V_{min}	minimum service speed, knots
V_{max}	maximum service speed, knots
$V_{o_{min}}$	minimum operational speed, knots
$V_{o_{max}}$	maximum operational speed, knots
V_s	stall speed (equivalent airspeed), knots
W	airplane weight, lb
w	incremental velocity along z-axis, ft/sec

LIST OF SYMBOLS (continued)

w_g	gust velocity along z-axis, ft/sec
x	body axis, longitudinal, origin at c.g.
y	body axis, right wing, origin at c.g.
$Y(s)_{cs}$	transfer function for airplane control system from control stick to control surface, rad/in
z	body axis, down, origin at c.g.
Z_{θ_1}	small zero in θ/F_s, $= -1/T_{\theta_1}$, rad/sec
Z_{θ_2}	large zero in θ/F_s, $= -1/T_{\theta_2}$, rad/sec
Z_{h_1}	smallest zero in h/F_s, $= -1/T_{h_1}$, rad/sec
Z_{h_2}	intermediate zero in h/F_s, rad/sec
Z_{h_3}	largest zero in h/F_s, rad/sec
Z_i	$= \frac{1}{M} \frac{\partial Z}{\partial i}$, $i = \alpha, u, q, \delta_e, \delta_h, \dot{\alpha}$
α	angle of attack, angle between x-axis and projection of air velocity vector in x-z plane, rad, deg
β	sideslip angle, angle between air velocity vector and its projection in x-z plane, rad, deg
γ	flight path angle, angle between velocity vector and horizontal, deg
$d\gamma/dV$	flight path stability parameter, steady state change in γ with V at constant throttle handle position, deg/knot
Δ	incremental
δ	control deflection
δ_e	elevator deflection, deg, rad, TE down = +
δ_{ES}	pitch control stick deflection (elevator stick), at stick grip, in, aft = +
δ_h	horizontal tail deflection, rad, deg, TE down = +
δ_e/δ_{ES}	gearing from control stick or column to pitch control surface, gain, rad/in, deg/in

δ_{ES}/F_s	gradient of stick deflection vs force, in/lb
ζ	damping ratio
ζ_{sp}	damping ratio of short period mode
ζ_p	damping ratio of phugoid mode
θ	pitch attitude, angle between x-axis and horizontal, deg
$\dot{\theta}$	time rate of change of θ, often used incorrectly for body pitch rate q, deg/sec
$\ddot{\theta}$	second derivative of θ, often uses incorrectly for body pitch angular acceleration, $\dot{q}$, deg/sec^2
λ	turbulence wave length, ft
λ	root of characteristic equation, usually real, rad/sec
λ_{sp_1}	most positive real root of short period mode
λ_{sp_2}	most negative real root of short period mode
λ_{csp_1}	most positive real root of short period mode with speed held constant
λ_{csp_2}	most negative real root of short period mode with speed held constant
$\lambda_{sp_{2_{CRIT}}}$	value of λ_{sp_2} (negative) for which pilot rating does not change for larger negative λ_{sp_2} (3.2.1.3)
ρ	air density, slug/ft^3
σ	real part of a complex root
σ	standard deviation, root-mean-square (rms) from the mean of a quantity
$\sigma_u, \sigma_v, \sigma_w$	rms of u_g, v_g, w_g, ft/sec
σ_V	rms of total gust velocity, ft/sec
τ	time constant, sec
$\tau_{p_1}, \tau_{p_2}, \tau_{p_3}$	time constants in pilot model
τ_d	time delay in pilot model, sec

LIST OF SYMBOLS (concluded)

τ_e	time delay in equivalent system model, sec
ϕ	bank angle, angle between y-axis and intersection of y-z plane with horizontal (about x-axis), deg, bank to right (right wing down) = +
ϕ_{PL}	pilot lead (phase of pilot model excluding time delay), deg
ω	frequency, imaginary part of complex root, rad/sec
$\omega_{n_{sp}}$	undamped natural frequency of short period mode with speed held constant, rad/sec
$\omega_{n_{csp}}$	undamped natural frequency of phugoid mode, rad/sec
$\measuredangle$	angle of, phase angle of

ABBREVIATIONS

A	acceptable (pilot rating, Ref. 28)
AP	acceptable poor (pilot rating, Ref. 28)
BW	bandwidth frequency
c.g.	center of gravity
CAS	calibrated airspeed
CCV	control configured vehicle
FCS	flight control system
FTD	flare and touchdown
HZ	hertz, cycles per second
ILS	instrument landing system
LAHOS	landing approach higher order system, refers to investigation of Ref. 8
mac	mean aerodynamic chord
MAT	maximum augumented thrust
PCP	pitch control power
PIO	pilot induced oscillation
PR	pilot rating
PR_{CRIT}	pilot rating for $\lambda_{sp2_{CRIT}}$ (3.2.1.3)
RA	resonant amplitude
RSSAS	relaxed static stability augumentation system
SAS	stability augumentation system
SST	supersonic transport
TE	trailing edge
U	unacceptable (pilot rating, Ref. 28)

SECTION I
INTRODUCTION

During recent years substantial work has been done to revise and improve the Military Flying Qualities Specification for Piloted Aircraft. The basis for these revisions has been data obtained from ground-based simulators, in-flight simulators or variable stability aircraft, and a wide range of experimental and operational aircraft, both civil and military. A major revision of the specification was initiated in 1966 by Cornell Aeronautical Laboratory under Air Force contract which culminated in MIL-F-8785B(ASG) (Ref. 1) and its accompanying Background Information and User Guide (Ref. 2). Additional work since has led to proposed revisions (Ref. 3, 4), with a revised specification MIL-F-8785C (Ref. 5) recently released.

Though some of this work has addressed the problems of airplane and control system combinations and higher order dynamics (Ref. 5, 6, 7, 8), no comprehensive criteria have been developed for the design of the advanced control systems that are beginning to be found in modern aircraft, particularly fighter aircraft. The capabilities for design, development and production of advanced technology flight control systems have outstripped the specification criteria defining the flying qualities requirements.

The reason for this situation seems reasonably straight-forward. The relatively simple augmentation systems considered in the 1969 revision of the flying qualities specification fell within the framework of conventional flying qualities of unaugmented aircraft. These systems did not fundamentally alter the transfer functions describing the airplane dynamics, nor the significance of the various modes of motion (i.e., short period, phugoid, Dutch-roll, etc.). However, when the door is opened to use the technology that was available then and has developed since, the range of possibilities for altering airplane characteristics becomes so large that new ways must be found to map out flying qualities criteria.

For example, consider the case where a significant amount of attitude feedback is introduced to the elevator, a feedback (C_{m_θ}) not

inherent in the unaugmented aircraft. The normal significance of the short period and phugoid modes is altered, and the airplane response to stick inputs assumes the form of an attitude command system, which one rapidly finds intolerable for maneuvering. An obvious cure is to use pitch rate feedback for augmentation while maneuvering, and only engage attitude feedback when flying in trim with zero stick force. Automatic trim is usually included as well. This concept is called a rate-command/attitude-hold system, often referred to as control wheel steering. It produces an airplane with zero speed stability, zero stick force per g in stabilized turns, and a nonlinear response with one set of dynamics for disturbances about trim and another set for maneuvering, all in contradiction to MIL-F-8785B requirements. If we credit Bihrle's theory of stick pumping (Ref. 10 and 11) with some veracity, then we have an airplane which precludes the pilot from using an important cue or piloting technique. There are no established flying qualities requirements for such systems, yet they are flying in airplanes today.

To establish flying qualities requirements for highly augmented airplanes, the wide range of potential variations offered by the use of recent control concepts must be considered. Some of these are six degree of freedom control for decoupling airplane motions, gust alleviation, ride qualities, and maneuver load alleviation; or CCV concepts such as relaxed static stability (RSS) or the variable camber wing for improved performance; or the multi-mode control which digital flight control computers are capable of providing. The advances in electronics, particularly with respect to cost, weight and reliability, are allowing consideration of new concepts and approaches to flight control system design. These in turn have opened up a new spectrum of possible flying qualities requiring consideration in specification criteria.

Because of its complex nature, the problem of developing flying qualities criteria for highly augmented aircraft needs to be divided into lesser more tractable tasks. The current study was funded by the Air Force to examine the safety assurance aspects of the specification criteria, particularly the requirements for airplanes with relaxed static stability (RSS) or c.g.'s located aft of the neutral point such as the General Dynamics F-16 or the Boeing YC-14. With respect to the use of

high levels of augmentation, flight safety aspects divide into several broad categories.

1) Validity of existing criteria
2) Need for new criteria
3) Survival under failure conditions
4) Protection for latent failures
   a) Hardware
   b) Generic

Each of these is discussed briefly below.

Existing established specification criteria may be invalid when applied to conditions associated with high levels of augmentation. For example, the requirement for speed stability as demonstrated by a stable pitch control vs. airspeed gradient is invalid when applied to an attitude hold/rate command system as it would have a zero gradient but good speed stability if $d\gamma/dV < 0$. Such criteria need to be modified so that they are neither over restrictive, resulting in unnecessary system complexity, or under restrictive, resulting in unsafe conditions.

New criteria are needed where augmentation systems introduce new facets which have not been dealt with previously. An example would be the use or incorporation of "relaxed static stability" to reduce maneuvering and trim drag, with the augmentation system relied upon for stability. With neutral stability at supersonic speeds, the c.g. could be well aft of the neutral point at low speeds. New requirements are needed for acceptable levels of stability after augmentation failures, for control power and rate limits, and for high angle of attack conditions to avoid departures and loss of control.

Survival under failure conditions is the principal subject of concern in a flight safety oriented study, hence effort centers on Level 2 and Level 3 flying qualities. Of primary concern are the ability to survive the immediate failure effects and transients, the ability to get home, and the ability to safely land the airplane. Also of concern is the ability to safely eject following the failure, as considered by MIL-F-9490D (Ref. 12). Of these, clearly a most critical task and deserving of attention is that of approach and landing.

Latent failures assume particular significance for highly augmented aircraft, since their flight control systems will usually be multiply redundant and more capable of covering up the effect of failures. A failure can go undetected until the situation deteriorates to the point of catastrophic consequences. There are generally two types of latent failures: those of hardware which go undetected either because of redundancy or because the particular system component or mode has not been exercised; and those which are generic to a particular characteristic associated with the augmentation system and could be called design deficiencies. Hardware failures are primarily the province of MIL-F-9490D (Ref. 12), though appropriate warning of such failures relates to MIL-F-8785. The generic failures are concerned with control requirements and clearly fall in the domain of MIL-F-8785. Criteria to prevent control saturation, and the need for large-amplitude stability for statically unstable aircraft (unaugmented) fall in this category. So do criteria for normal acceleration limiting or angle of attack and sideslip limiting for aircraft with relaxed static stability, or for aircraft with rate-command/attitude-hold systems which can mask the approach to envelope extremes.

1.1 Relaxed Static Stability (RSS)

Since flying qualities requirements for relaxed static stability comprise the primary subject matter of this report, it is appropriate to define relaxed static stability at this point. There are two general forms that relaxed static stability can take, longitudinal stability and directional stability. This report is only concerned with the former, so all reference to relaxed static stability (RSS) is to be taken as meaning the longitudinal case.

Relaxed static stability refers to an airplane which, in order to obtain performance benefits either in level or maneuvering flight, has its center of gravity located aft of the c.g. range normally chosen. Normally, the aft limit of the c.g. range is chosen to assure good or acceptable longitudinal stability, dynamic response, maneuver characteristics, and stall recovery, while the forward limit is chosen to provide

controllability for trim and nose-wheel lift-off (Ref. 13). With the requirement for aerodynamic stability relaxed and the c.g. sufficiently aft, the gradient of pitching moment with angle of attack (C_{m_α}) is positive or unstable. This unstable gradient means that as angle of attack increases, a nose down elevator or tail deflection is required to balance the airplane. The net result is an up-load on the tail which increases lift efficiency and decreases drag, especially trim drag. The horizontal tail, now sized for control power, can generally be smaller. Fuselage and landing gear can be shortened, the wing made smaller, and a significant aggregate weight saving realized.

A moderate amount of relaxed static stability is presently well-accepted, provided the unaugmented airplane meets the Level 2 or 3 requirements, and appropriate augmentation is incorporated to provide normally good flying qualities or meet the Level 1 requirements. However, airplanes are now being considered with more extreme amounts of relaxation, with c.g. range well aft and the controls-fixed airplane actually unstable, with resulting requirements on the augmentation system as well as the allowable instability.

The benefits in cruise efficiency and maneuver capability, though most significant for supersonic aircraft, are still important for subsonic ones. Estimates of reductions in fuel consumption range from 10 to 15%. For aircraft to have sustained supersonic capability, relaxed static stability is generally recognized as a necessity. Kehrer (Ref. 14, 15, and 16) gives an excellent description of the benefits and technical problems associated with the use of RSS for both supersonic and tactical aircraft. A more detailed definition of relaxed static stability, its benefits and effects, is found in the introduction to Appendix B of this report.

1.2 Specific Study Approach

The program performed and reported upon had the following main tasks, and subtasks:

1) Evaluate accident/incident data.

2) Identify areas of MIL-F-8785B that can be revised to increase flight safety.

3) Review available flying qualities data, identify deficient areas in MIL-F-8785B, and perform analyses to revise or develop new criteria.

4) Conduct ground simulation to provide data and develop criteria for deficient areas in MIL-F-8785B.

5) Propose revisions with substantiating data for MIL-F-8785B, in MIL Standard and Handbook format.

6) Define research required to generate additional data needed to validate tentative criteria.

Specific areas examined in the study included the following, with emphasis on requirements for fighter and attack (Class IV) aircraft.

1) The interface between the Flying Qualities Specification, MIL-F-8785B, and the Flight Control System Specification, MIL-F-9490D.

2) Criteria for highly augmented unstable and neutrally stable aircraft under normal and failure state conditions.

   a) Parametric examination of control requirements, nonlinearities (limited to low non-stall angle of attack region), degraded higher order systems, and tolerable levels of airplane instability and flight control system lags.

   b) Requirements for control authority, position and rate limits, as functions of turbulence and maneuver severity.

   c) Pilot workload and saturation.

The original intention was to examine in detail both approach and landing tasks and air combat tasks. However, the air combat phase was dropped in order to concentrate on the approach and landing phase which seemed more critical.

A substantial simulation program was conducted, augmented by a separate Boeing IR&D supported simulation program, to provide a data base for developing criteria for RSS airplanes in the approach and landing task.

The representative baseline airplane used for analysis and simulation was the F-111A, but considerable liberties were taken with the flight control system, to simplify it, or to make it more generic. The F-111A was selected because it has a highly augmented flight control system with sophisticated self-adaptive gains, because data on the aircraft was readily available, and because a CCV effort was currently underway by the Air Force under the AFTI-111 program.

The bulk of the analysis and simulator investigation was concerned with longitudinal characteristics. The criteria developed are primarily for those characteristics associated with the aft c.g. locations that produce unstable and neutrally stable aircraft in the longitudinal modes.

1.3 Report Organization

The organization of this report is designed to facilitate comparison with MIL-F-8785B (Ref. 1) or MIL-F-8785C (Ref. 5) and to facilitate incorporation of the material in the new MIL Standard and Handbook (Ref. 17 and 18). Section II describes the format and approach used in developing the proposed revisions, outlines the major revisions, their basis, and how they relate to the new Standard and Handbook. It also assesses briefly the adequacy of the substantiation for the proposed revision. Section III contains the proposed revisions as suggested for the MIL Standard. Section IV contains the supporting data and background information for the Handbook. Section V defines the additional research required to substantiate the tentative proposed revisions. Sections VI and VII present conclusions and recommendations. Sections I through VII, together with References, comprise Volume I.

The study results, proposed new or revised flying qualities criteria and supporting data for the MIL-Standard and Handbook, are presented in the body of this report, Volume I, Section 1 through 7. However, the bulk of the report is found in the Appendices in Volumes II and III which present results and data from the various substudies and investigations performed. Appendix A contains the statistical data from the analysis of accident/incident reports. Appendix B develops the characteristics of airplanes with relaxed static stability, examines

existing flight test and simulator data pertinent to criteria for relaxed static stability, and analyzes the results of the simulator study to develop criteria both in parametric form and using a modified closed-loop Neal-Smith (Ref. 7) frequency-response approach. Appendix C describes the ground simulator, the procedures used to generate the data analyzed in Appendix B, defines the evaluation configurations, and gives the pilot rating data. Appendix D presents some lessons learned from the Boeing YC-14 flight test program. Results of a study to improve the interface between MIL-F-8785B and MIL-F-9490D are presented in Appendix E. Appendix F summarizes the linearized longitudinal equations and defines relationships among equations and transfer functions in two and three degrees of freedom. Appendixes A through F, together with References, comprise Volume II. There is one set of references for this report, and it will be found at the end of both Volumes I and II.

The pilot comments, in full detail, for all configurations evaluated by the three pilots in the ground simulator investigation, are found in Appendix G which comprises Volume III.

The paragraph numbers and typography used in Sections III and IV for the proposed revisions are those of the preliminary MIL Standard and Handbook (Ref. 17 and 18).

To avoid confusing paragraph numbers with section or subsection numbers of this report, only major subsection numbers are used in Sections I, II, and V through VII of this report, and reference to them always calls out a section number (i.e., Section 1.2). Appendices sections and subsections are clearly distinguishable by the initial letter designation (e.g., A.1.2).

SECTION II
FORMAT, APPROACH, AND SUMMARY OF PROPOSED REVISIONS

2.1 Model for Paragraph Numbers, Standard, and Handbook

The proposed revisions and new additions to the Military Specification of Flying Qualities of Piloted Airplanes as presented in Sections 3 and 4 are in MIL Standard and Handbook format. Though a proposed specification in the new MIL Standard and Handbook format has now been published in preliminary form by Hoh, et al. (Ref. 17 and 18), this specification was not available at the time this report was written. Though the paragraph numbering system and titles follow Reference 17 and 18, the organization of the proposed revisions was based on a preliminary draft of the Standard (Ref. 19) while the technical content and criteria for the requirements were based on MIL-F-8785C (Ref. 5). Since the later publications by Hoh, et al. (Ref. 17 and 18) are organized somewhat differently from the earlier Reference 19, are complete and have received rather wide distribution, it was felt worth the effort to convert the numbering system of the revisions proposed in this report to those of References 17 and 18. However, the content of the proposed revisions have been left substantially unchanged. Thus, in a few places the organization of paragraphs does not follow References 17 and 18 precisely. For example, modifications for relaxed static stability to the PIO (3.2.2) and Residual Pitch Oscillation (3.2.3) requirements are found in the requirement for Pitch Attitude Response to Pitch Controller (3.2.1), as they were in Reference 19.

The model for the MIL Standard was that of Reference 19, but except for paragraphs on pitch axis control forces, no model was available for the MIL Handbook as such when this report was written. Thus, most of the revisions and additions for the MIL Handbook are based in content on MIL-F-8785C (Ref. 5) and the Background Information and User Guide for MIL-F-8785B (Ref. 2).

2.2 Approach to Revision

The primary emphasis in the proposed revisions and additions to the military flying qualities specification is placed on incorporating requirements for airplanes with relaxed static stability (RSS) in pitch. The need for this incorporation is rather obvious. On one hand, the total treatment of RSS in the flying qualities specifications (Ref. 1 or 5) is mostly confined to the requirement for longitudinal static stability (3.2.1.1 of either Ref. 1 or 5): Reference 1 prohibited instability; Reference 5 allows it, "time to double amplitude shall not exceed 6 seconds for Level 3", subject to approval by the procuring agency. On the other hand, the YF-16 prototype and the F-16, now operational, were both designed to have static instability at low speed with control surfaces fixed, and incorporate full-time augmentation and fly-by-wire.

A number of investigations have been made of relaxed static stability, analytical and using ground and flight simulation. Most, however, have just been concerned with the effect on dynamics of shifting the c.g. aft, and few have provided enough data to fully define the airplane characteristics. It came to the author's attention many years ago that RSS flying qualities depended on more than just the stability level. At the Naval Air Test Center at Patuxent River, Md., flight tests were conducted with an A3J airplane with c.g. located to give neutral static stability, and flying qualities were found very bad. On the other hand, flight tests in a B-26 variable stability airplane with δ_e/α gain adjusted to give neutral static stability showed reasonably good flying qualities. The question was, "What is the difference? Why?" These questions have never been answered, but presumably they involve differences other than static stability.

A simulator experiment was run, as a main part of this investigation, to find the effects of the various parameters in the θ/F_S transfer function on flying qualities with RSS. The assumption, based on the work of Neal and Smith (Ref. 6) and borne out by the simulation results, was that parameters in the θ/F_S transfer function would define nearly completely the flying qualities of an RSS airplane.

The simulation is described in Appendix C, with results analyzed in Appendix B. The key element in the simulation experiment was that parameters in the θ/F_S transfer function were varied independently to isolate their individual effects. The results have led to a new way to look at RSS and to define meaningful criteria. These criteria show a powerful influence of a number of parameters and not just the static stability or time to double amplitude. The results have been used to define revisions and additions to the flying qualities specification.

2.3 Summary and Basis for Proposed Revisions

It was not easy to decide how to incorporate revisions into the flying qualities specification (MIL Standard and Handbook) for relaxed static stability (RSS), since to do so requires a substantial departure from the philosophy of MIL-F-8785B and MIL-F-8785C. It was decided to incorporate RSS as a separate set of alternate requirements which the procuring agency could either allow or disallow, and if allowed, then the airplane manufacturer would have the option of selecting the alternate requirements as a whole if he wanted to take advantage of RSS. To implement this approach, specific requirements were developed and appended to each existing requirement that was affected by RSS. These requirements are identified by the use of "RSS" in the title, generally as the first word.

The use of RSS generally means that stability augmentation will be required for Level 1, and with this augmentation turned OFF or failed, the Level 2 and Level 3 requirements will be met either with the unaugmented aircraft or with an essential SAS (back-up or hard SAS) of adequate reliability. Thus each requirement generally has two parts, one dealing with the augmented normal state, the other dealing with the augmentation failure state. With the exception of control power, the normal state requirements for RSS are generally the same as those for stable aircraft. The failure state requirements, on the other hand, are generally quite different for RSS than the usual Level 2 and Level 3 ones for stable aircraft.

Besides the revision for RSS, a few revisions are proposed that do not stem directly from the investigation of RSS. These revisions together with the RSS revisions are outlined briefly below. It should be noted that the revisions, though following the numbering system of References 17 and 18, are based primarily on the technical content of MIL-F-8785C.

MIL Standard Paragraph	Title
3.1.7	Dangerous Flight Conditions
3.1.11	Relaxed Static Stability (New)
3.2.1	Pitch Attitude Response to Pitch Controller
3.2.2	Pilot Induced Oscillations in Pitch
3.2.3	Residual Pitch Oscillations
3.2.8	Pitch Axis Control Power
3.2.9	Pitch Axis Control Forces
3.2.10	Pitch Axis Control Displacements
3.8.1	Cross Axis Coupling in Roll Maneuvers
3.8.4	Stalls
3.8.5	Departures and Spins
3.8.6	Control Coupling for Failures with RSS (New)

Skipping 3.1.7 for the moment, general requirement 3.1.11 provides the basic definition of relaxed static stability (RSS). It also defines the application of Flying Qualities Levels to airplanes with RSS for normal and failure states, whether RSS is to be allowed, and if so, the reliability requirements including those for airplanes that do not meet the minimum Level 3 requirements with control surfaces fixed (> Level 3, worse than Level 3). The possibility of worse than Level 3 with all stability augmentation failed, and the allowance of worse than Level 3 provided its probability of occurrence is sufficiently small, are the main points of departure from the philosophy of MIL-F-8785C and its predecessor MIL-F-8785B, neither of which allowed worse than Level 3 except as a Special Failure State.

Coming back to 3.1.7, the requirement for devices which indicate, warn, prevent, or aid recovery from dangerous flight conditions is modified for RSS. First, the restriction on the use of such devices is removed. Second, warnings for specific conditions associated with RSS are specified.

The requirement for pitch attitude control (3.2.1) is the primary requirement treating the effects of RSS on stability and response characteristics of the unaugmented airplane, or one with essential SAS. The requirement is stated in two forms. One is in terms of parameters in the θ/F_S transfer function, and can be appropriately applied to lower order equivalent system models. The other is a closed-loop frequency response approach to θ/F_S, and can be appropriately applied to higher order systems directly as well as the lower order traditional airplane. Included in 3.2.1 are the modifications for RSS to the PIO (3.2.2) and residual oscillation (3.2.3) requirements. These are included because they were part of the pitch attitude response requirement of Reference 19 which served as the model for the MIL Standard, and they were not readily separable later. Also included are some RSS-related requirements on the phugoid mode and speed stability ($d\gamma/dV$).

The requirement on pilot induced oscillations (3.2.2) is only modified to the extent found as part of 3.2.1. The Level 2 and 3 requirements for pitch augmentation failure states are somewhat relaxed at low frequencies because, for a statically unstable airplane, there will always be an inherent limit cycle. Thus the PIO requirement is relaxed to allow this limit cycle, with amplitude and frequency consistent with the level of flying qualities.

A new residual oscillation requirement (3.2.3) has been proposed, based on new data as described in Appendex E, and totally unrelated to RSS requirements. However, the residual oscillation requirements for Level 2 and Level 3 are also modified for RSS to the extent found in 3.2.1. This relaxation is necessary to allow the limit cycle inherent to RSS as described in the previous paragraph concerning PIO's.

Pitch control power requirements (3.2.8) are especially significant for RSS airplanes, and these requirements apply to both normal and failure states. They are generally more stringent than requirements for stable aircraft. Specific quantitative requirements are stated for both control authority and control rate, with critical conditions being approach and landing in turbulence, rolling maneuvers, and recovery from stall and high angle of attack flight. Use of angle-of-attack limiting and departure prevention systems is encouraged, and if pitch-up is too severe, so there is inadequate control margin, then such a system with specified minimum reliability is required.

Pitch control force requirements (3.2.9) impose no limitations on the gradient of pitch control force with speed in unaccelerated flight (F_S/u) in the proposed MIL Standard and Handbooks (Ref. 17 and 18). Since there are data which show that excessive values of this gradient will degrade flying qualities, quantitative requirements on F_S/u are proposed based on the available data. MIL-F-8785B and its successor MIL-F-8785C required F_S/u to be negative as evidence of static stability and speed stability. However, for highly augmented aircraft, F_S/u is not necessarily related to stability. So, requirements on F_S/u are proposed, unrelated to speed or static stability or RSS, to insure that the gradient will not get too large either positively or negatively, with a zero gradient included in Level 1.

Pitch control force requirements (3.2.9), though unaffected by the presence of RSS in airplane normal states, are substantially affected for statically unstable aircraft. Force levels must be especially low, in both unaccelerated and maneuvering flight, to enable the pilot to insert the specialized inputs (pulses) required for unstable or neutrally stable aircraft. In addition, steady-state or low frequency gradients (F_S/u, F_S/n) will generally reverse for sufficiently unstable airplanes with failed augmentation. So the normal Level 2 and 3 requirements of 3.2.9 are significantly modified to allow for the very low and reversed gradients associated with RSS under failure condition of the augmentation system. At the same time, requirements are imposed to preclude forces

from becoming too large, and to preserve integrity at higher frequencies to avoid objectionable pilot induced oscillations. Pitch trim requirements are made more severe for RSS conditions to help keep force levels low.

Special requirements on control displacements (3.2.10) apply to RSS airplanes. There must be sufficient cockpit control travel to provide the control power margin required under 3.2.8. In addition, steady-state and low frequency control displacements reverse for unstable aircraft, so requirements for initial and steady-state deflection in the same sense (direction) for RSS failure states are eliminated. Control sensitivity ($M_{\delta_{ES}}$), if too low in RSS failure states, can cause severe degradation of flying qualities. Adequate sensitivity is required.

Maneuvers involving motions about combined axes (3.8), particularly rolls (3.8.1), stalls (3.8.4), departures and spins (3.8.5), pose especially critical conditions for RSS airplanes with respect to control power, regardless of airplane state (normal or failure). Special requirements are formulated for roll maneuvers, and for high-angle-of-attack conditions. These include special requirements on angle-of-attack limiting and departure prevention systems and their reliability. For failure states that result in RSS conditions, pitching motions that result from roll control inputs can have a very deleterious effect, so restrictions are placed on roll inputs propagating into pitch.

2.4 Substantiating Data

The criteria on attitude response to pitch control inputs for RSS airplanes (3.2.1.3) are reasonably well supported by both ground simulator and flight test data for approach and landing. The weak link is on the effect of control sensitivity. For flight conditions other than approach and landing, there are almost no data.

Pitch-axis control power criteria for RSS airplanes (3.2.8.6) rest on the barest minimum of data, both for approach and landing and for stall and high angle of attack. The approach and landing data are all from the simulations of this investigation. Stall data are based on

control useage data from flight tests of three airplanes, plus a simulator investigation of control power required for one airplane.

Criteria on pitch-axis control forces and displacements for RSS airplanes (3.2.9.9 and 3.2.10.4) are based mostly on extrapolation of data taken with pilot-selected optimum force gradients for approach and landing. No data are available on independent variations of control force and deflection gradients, for approach and landing or for up-and-away flight in such tasks as cruise and air combat (tight tracking tasks).

In combined axes and high angle of attack flight (3.8) the control power margin required for RSS airplanes is critical. The criteria are based on the level flight stall data since no data for accelerated stalls or rolling maneuvers are currently available.

2.5 Table of Contents for MIL Standard and Handbook

The following table of contents, taken from Reference 18, lists all paragraphs found in the Handbook except those under 3.5, 3.6, 3.7 and 5. These latter are not germane to present use. Where paragraph numbers appear to be missing, either they are found in Reference 17 but without supporting data in Reference 18 (e.g., 3.2.4), or they are simply not used (e.g., 3.2.6). This listing of the requirements by number and title will be found quite helpful in seeing how the various proposed revisions and additions fit into the MIL Standard and Handbook, and in identifying paragraphs called out only by number in Sections III and IV.

3.2.3 Residual Pitch Oscillations

3.2.7 Pitch Axis Response to Other Inputs

- 3.2.7.1 Pitch axis response to auxiliary controls
- 3.2.7.2 Pitch axis response to failures
- 3.2.7.3 Pitch axis response to configuration or control mode change
- 3.2.7.4 Pitch axis response to stores release
- 3.2.7.5 Pitch axis response to armament delivery
- 3.2.7.6 Buffet

3.2.8 Pitch Axis Control Power

- 3.2.8.1 Pitch axis control power in unaccelerated flight
- 3.2.8.2 Pitch axis control power in maneuvering flight
- 3.2.8.3 Pitch axis control power in takeoff
- 3.2.8.4 Pitch axis control power in landing
- 3.2.8.5 Pitch axis control power for other conditions

3.2.9 Pitch Axis Control Forces

- 3.2.9.1 Pitch axis control forces -- steady-state control force per g
- 3.2.9.2 Pitch axis control forces -- transient control force per g
- 3.2.9.3 Pitch axis control forces -- control force variations during rapid speed changes
- 3.2.9.4 Pitch axis control forces -- control force vs. control deflection
    - 3.2.9.4.1 Stead-state control force/deflection gradient
    - 3.2.9.4.2 Transient control force vs. deflection
- 3.2.9.5 Pitch axis control force -- control centering and breakout forces
- 3.2.9.6 Pitch axis control forces -- free play
- 3.2.9.7 Pitch axis control force limits

- 3.2.9.7.1 Pitch axis control force limits -- takeoff
- 3.2.9.7.2 Pitch axis control force limits -- landing
- 3.2.9.7.3 Pitch axis control force limits -- dives
- 3.2.9.7.4 Pitch axis control force limits -- sideslips
- 3.2.9.7.5 Pitch axis control force limits -- recovery from post-stall gyrations and spins
- 3.2.9.7.6 Pitch axis control force limits -- failures
- 3.2.9.7.7 Pitch axis control force limits -- control mode change

3.2.9.8 Pitch axis trim systems

- 3.2.9.8.1 Pitch axis trim systems -- rate of operation
- 3.2.9.8.2 Pitch axis trim systems -- stalling of trim systems
- 3.2.9.8.3 Pitch axis trim systems -- irreversibility

3.2.10 Pitch Axis Control Displacements

- 3.2.10.1 Pitch axis control displacements -- takeoff
- 3.2.10.2 Pitch axis control displacements -- maneuvering
- 3.2.10.3 Pitch axis control displacements -- gust regulation
- 3.3.1.2 Vertical axis response to attitude change -- steady-state response
  - 3.3.1.2.1 Vertical axis steady-state response -- aircraft with designated flight path controller

SECTION III

PROPOSED REVISIONS - MIL STANDARD

The proposed revisions to the military flying qualities specifications for piloted airplanes are based in organization on a preliminary draft of the MIL Standard (Ref. 19), and in contents primarily on MIL-F-8785C (Ref. 5). A later and complete preliminary version of both the MIL Standard and Handbook (Ref. 17 and 18) became available shortly prior to publication of this report. Because this later version has been widely distributed, the paragraph numbering system and titles used in this report were changed to conform to those of the new version (Ref. 17 and 18). The organization of the paragraphs was also changed, where easy to do, but some differences will be noted. However, the proposed revisions are generally self contained and additive, so future changes to the proposed revisions or the draft MIL Standard and Handbook can be made with minimum interaction.

Each major paragraph or set of related paragraphs is preceded by a summary which lists the affected paragraph and subparagraphs by number and name from the draft MIL Standard and Handbook (Ref. 17 and 18), and indicates the type of recommended action. The proposed revision or new material then follows. The proposed revisions or new material for the supporting Handbook are found in Section IV. The major proposed changes are outlined in Section II with Section 2.3 providing an executive summary. The germane parts of the table of contents from the draft Handbook (Ref. 18) are presented in Section 2.5 to help show how the proposed revisions integrate into the MIL Standard and Handbook.

3.1.7 <u>Dangerous Flight Conditions - New Addition</u>

3.1.7 Dangerous Flight Conditions

3.1.7.1 - 3.1.7.2 (No revision recommended)

3.1.7.3 RSS warning and indication. (New addition)

3.1.7.3 <u>RSS warning and indication</u>. The requirements of 3.1.7.1 apply to conditions of relaxed static stability as identified in 3.1.11 and

defined in 3.1.11 of the Handbook, but the requirements of 3.1.7.2 are replaced by the following for warning of dangerous flight conditions resulting from relaxed static stability.

Three levels of warning are required for airplanes with relaxed static stability, as follows.

a. In the event that a flight control system failure will, when followed by a subsequent failure, result in the need for restricting the flight envelope or operation of the airplane to avoid dangerous flight conditions, then a clearly distinguishable warning (a caution) shall be given to the pilot so that he may take corrective action, either to re-establish integrity of the FCS or to restrict flight operations appropriately.

b. In the event that a flight control system failure will result in the need for restricted flight operation of the airplane in order to avoid dangerous flight conditions, then a clearly discernible warning, of a superior nature to that of (a) above, shall be given the pilot so that he may take immediate action.

c. In the event that a flight control system failure will place the airplane in a dangerous flight condition, where structural damage or loss of control is possible, a clearly discernible warning, different from (b) above, shall be given so the pilot can take immediate appropriate action.

Reliability requirements for the above warnings shall be as follows ________________.

The requirements in 3.1.7.2 with respect to functional performance, inadvertent operation, and functional failure shall apply. Nuisance operation shall not be possible for any Level of flying qualities.

3.1.11 <u>Relaxed Static Stability - New Paragraph</u>

3.1.11 Relaxed Static Stability (RSS). (New addition)

3.1.11.1 RSS Normal-State flying qualities. (New addition)

3.1.11.2 RSS Failure-State flying qualities. (New addition)

3.1.11.2.1 RSS augmentation not affected. (New addition)

3.1.11.2.2 RSS augmentation affected. (New addition)

3.1.11 Relaxed static stability (RSS). Special alternate requirements are formulated applicable to the deliberate use of relaxed static stability (RSS). The alternate requirements are formulated on the basis that stability augmentation will be used to provide Normal-State flying qualities.

Quantitative requirements at present are only available for relaxed static stability in pitch, and are found in 3.2 and 3.8.

3.1.11.1 RSS Normal-State flying qualities. The Levels of flying qualities as specified in 3.1.5 apply to airplanes with relaxed static stability for the aircraft operating in a normal, unfailed state. Special requirements on control power (3.2.8), control forces (3.2.9), control displacements (3.2.10), and control coupling and flight at high angles of attack (3.8) must be met in addition.

3.1.11.2 RSS Failure-State flying qualities. Two categories of Failure States are defined for aircraft with relaxed static stability, those States where the failures do not involve or affect the components of the flight control augmentation system which augments the relaxed static stability, and those failures which do involve or affect such components. Requirement 3.1.11.2.1 applies to the former, requirement 3.1.11.2.2 to the latter.

3.1.11.2.1 Failure-State flying qualities - RSS augmentation not affected. For these Failure States, the Level of flying qualities shall be as specified in 3.1.6.

3.1.11.2.2 Failure-State flying qualities - RSS augmentation affected. For these Failure States which involve failure of the flight control augmentation system that stabilizes an inherently unstable airplane, the method of 3.1.6.1 applies, but the following changes and additions are made.

Failures of the flight control augmentation system can degrade flying qualities to worse than Level 3, and such types of failure are ______________.

3.2.1 Pitch Attitude Response to Pitch Controller - New Addition

3.2.1 Pitch Attitude Response to Pitch Controller

3.2.1.1 - 3.2.1.2. (Not considered for revision)

3.2.1.3 RSS Pitch Attitude Response to Pitch Controller. (New addition)

3.2.1.3 RSS pitch attitude response to pitch controller. Aircraft having relaxed static stability, as identified in 3.1.11 and defined in 3.1.11 of the Handbook, are required to meet 3.2.1.1 and 3.2.1.2 and also 3.2.2 and 3.2.3 for the flight control system in Normal State with pitch augmentation ON, and unfailed. For Failure States of the flight control system (pitch augmentation OFF or failed), the Level 2 and 3 requirements for pitch attitude response to pitch control input (3.2.1.1 and 3.2.1.2) and for PIO's (3.2.2) and residual oscillations (3.2.3) are modified to the following: ______________.

3.2.3 Residual Pitch Oscillations - Revision

3.2.3 Residual Pitch Oscillation. (Revision recommended)

3.2.3 Residual Pitch Oscillations. Any sustained residual oscillation shall not interfere with the pilot's ability to perform the tasks required in service use of the airplane. Any sustained residual oscillation, controls fixed or controls free, in calm air, shall not exceed ______________.

3.2.8 Pitch Axis Control Power - New Additions

3.2.8 Pitch Axis Control Power.

3.2.8.1 - 3.2.8.5. (Not considered for revision)

3.2.8.6 RSS pitch axis control power. (New addition)

3.2.8.6.1 Minimum control authority. (New addition)

3.2.8.6.2 Minimum control rate. (New addition)

3.2.8.6.3 Rolling maneuvers. (New addition)

3.2.8.6.4 Stall and high angle of attack. (New addition)

3.2.8.6 RSS pitch axis control power. Control authority, rate, and hinge moment capability have special requirements pertinent to the use of relaxed static stability, both for Normal States (pitch augmentation ON, and unfailed) and Failure States (pitch augmentation OFF or failed) of the flight control system.

The requirements of 3.2.8.1 through 3.2.8.5 shall be met with control authority, rate and hinge moment capability sufficient to provide a safe margin of control, over and above that normally required for stable aircraft, in order to recover from any pitch divergence due to relaxed static stability.

Specific requirements of 3.2.8.6.1 to 3.2.8.6.4 shall be met.

3.2.8.6.1 Minimum control authority. For both Normal and Failure States of the flight control system, the minimum control authority margin over and above the control required for trim, steady maneuvers, and failure transients or conditions shall be as follows for all altitudes, airspeeds, and normal accelerations where the airplane is characterized by relaxed static stability in pitch with control surfaces fixed: ________________.

3.2.8.6.2 Minimum control rate. The control rate available shall be adequate to avoid causing instability, divergence, or pilot induced oscillations for both normal and failure states of the flight control system, including transients precipitated by control mode changes, failures, and store release. This requirement applies to the prevention of loss of control and recovery from any situation for all maneuvering throughout the permissible flight envelope, including maneuvering appropriate to failure states.

For the critical condition of approach and landing in turbulence, for Normal and Failure States of and affecting the flight controls, in the atmospheric disturbances specified in 4.0, loss of control due to inadequate control rate shall be no more probable than ____________. Furthermore, for a maximum control input from either the pilot's pitch control or the pitch stability augmentation system, the

control surface rate shall provide at least an average pitch angular acceleraton rate, measured from trim to full control deflection, of the following:_____________.

3.2.8.6.3 <u>Rolling maneuvers</u>. In the rolling maneuvers specified in 3.8.1, and for at least ___________ successive maximum-performance bank to bank rolls between ______ and ________ degrees of bank angle, entered from the same conditions specified in 3.8.1, the control authority, rate, and hinge moment capability shall be sufficient to prevent divergence or loss of control for Airplane Normal States.

3.2.8.6.4 <u>Stall and high angle of attack</u>. In any Airplane Normal State or Failure State of 1.6.1 or 1.6.2 within the Permissible Flight Envelope, for all angles of attack from zero lift to _______,with full nose-down control the airplane shall exhibit a net nose-down pitching moment of sufficient magnitude to generate________rad/sec^2 nose-down angular acceleration.

Alternatively, a lesser nose-down (including nose-up) pitching moment shall be allowed at high angles of attack if a means or device is provided to limit the angle of attack, with sufficient reliability, to values below those where the above requirement for angular acceleration is not met. The probability of an angle of attack limiter failing to work shall be less than__________.

The same angular acceleration requirement applies for nose up pitching moments for negative angles of attack from zero lift to _________ with full nose up control. An alternative limiter of sufficient reliability is also allowed to help meet this large negative angle of attack requirement.

3.2.9 <u>Pitch Axis Control Forces - Revision and New Additions</u>

3.2.9 Pitch Axis Control Forces.

3.2.9.1 Pitch axis control forces -- steady-state control force per g. (Not considered for revision)

3.2.9.2 Pitch axis control forces -- transient control force per g. (Not considered for revision)

3.2.9.3 Pitch axis control forces -- variation with speed (New title)

3.2.9.3.1 Pitch control force variation with speed in unaccelerated flight. (New addition)

3.2.9.3.2 Pitch control force variations during rapid speed changes. (Same as previous 3.2.9.3)

3.2.9.4-3.2.9.8 (Not considered for revision)

3.2.9.9 RSS pitch control forces (New addition)

3.2.9.9.1 RSS pitch control forces in unaccelerated flight. (New addition)

3.2.9.9.2 RSS pitch control forces in maneuvering flight. (New addition)

3.2.9.9.3 RSS pitch control force limits and trim. (New addition)

3.2.9.3 Pitch axis control forces - variation with speed

3.2.9.3.1 Pitch control force variation with speed in unaccelerated flight. With the aircraft trimmed in unaccelerated flight at any speed and flight path angle, with throttle and trim not changed by the pilot, the variation of control force with speed shall be smooth. For speed changes from trim of ±15%, except the change need not exceed ±50 knots calibrated airspeed, ±0.1M, or the boundaries of the Service Flight Envelope, the following requirements shall be met ________.

3.2.9.3.2 Pitch control force variations during rapid speed changes. (This requirement is 3.2.9.3 of Reference 17, renumbered to allow its incorporation with new requirement 3.2.9.3.1 under 3.2.9.3. No change required except number, and title shortened by deleting word "axis.")

3.2.9.9 RSS pitch control forces

3.2.9.9.1 RSS pitch control forces in unaccelerated flight. For flight control system Normal States (augmentation ON, unfailed) the requirements are unchanged from 3.2.9.3.1. For flight control system Failure States (augmentation OFF or failed) no control force gradient with speed shall be so large, stable or unstable, as to interfere with the pilot's ability to control the airplane. Nor shall the magnitude of the control force change from trim, in the speed interval specified in 3.2.9.3.1, be so large as to interfere with the pilot's ability to control the airplane.

3.2.9.9.2 RSS pitch control forces in maneuvering flight. The requirements for Normal States (augmentation ON, unfailed) of the flight control system are unchanged from those of 3.2.9.1, 3.2.9.2, 3.2.9.3.2, and 3.2.9.4.

For Failure States (augmentation OFF or failed) of the flight control system, the requirements of 3.2.9.1, 3.2.9.2, 3.2.9.3.2, and 3.2.9.4 are modified as follows.

The variation of pitch control force with steady state normal acceleration (3.2.9.1), whether stable or unstable, shall not be so large as to be objectionable or interfere with the pilot's ability to control the aircraft. The numerical requirements or requirements for linearity of pitch control force with steady state normal acceleration of 3.2.9.1 do not apply for RSS with failures (augmentation OFF or failed).

The dynamic requirements of 3.2.9.2 shall be met for frequencies above 1 rad/sec.

The requirements of 3.2.9.3.2 shall be met but the pilot technique shall be that appropriate for the control of aircraft with relaxed static stability. (Note: 3.2.9.3.2 is 3.2.9.3 of Ref. 17 and 18)

The requirement of 3.2.9.4 shall be met, except that the gradient of pitch control force per unit of pitch control deflection shall not be so large as to be objectionable or interfere with the pilot's ability to control the aircraft.

3.2.9.9.3 RSS pitch control force limits and trim. The requirements for Normal States (augmentation ON and unfailed) of the flight control system

are unchanged from those of 3.2.9.7.1 through 3.2.9.7.7, 3.2.9.8, and 3.2.9.8.1 through 3.2.9.8.3

With Failure States (augmentation OFF or failed) of the flight control system, the control forces required for take-off, landing, dives, steady sideslips, and control mode changes shall not be so large as to be objectionable or interfere with the pilot's ability to control the aircraft.

In addition, it shall be possible for the pilot to trim the control forces to zero within______seconds, under all Failure States which involve loss of pitch augmentation that have more than a remote probability of occurrence, without the pilot removing both hands from the pitch controls. This requirement applies to runaway trim.

3.2.10 <u>Pitch Axis Control Displacements - New Additions</u>

3.2.10 Pitch Axis Control Displacements

3.2.10.1-3.2.10.3 (Not considered for revision)

3.2.10.4 RSS pitch control displacements. (New addition)

3.2.10.5 RSS pitch control displacements for Failure States. (New addition)

3.2.10.4 <u>RSS pitch control displacements</u>. Special requirements on control displacements apply to airplanes with relaxed static stability.

In take-off, the requirement of 3.2.10.1 shall be met with at least the following control power margins____________.

In all types of landings for which the airplane is designed, the pitch control travel shall be such that the control margins of 3.2.8.6.1 are available.

3.2.10.5 <u>RSS pitch control displacements for Failure States</u>. The following modified and special requirements apply to Failure States (pitch augmentation OFF or failed) of the flight control systems.

The requirement of 3.2.10.2 for steady state incremental control deflection in the same sense as initial deflection need not be met, provided the requirements of 3.2.1.3 are met at all steady load factors

and pitch rates in turns and pullups for which the aircraft is designed, and provided the control margins of 3.2.8.6 are also met in these turns and pullups.

Control displacements shall not be so large as to be objectionable or interfere with the pilot's ability to control the aircraft in pitch.

Control sensitivity, in terms of pitch angular acceleration per inch of pitch control deflection, shall not be so small that it significantly degrades the pilot's ability to control the aircraft, nor so large that it precipitates pilot induced oscillations. For the approach and landing phase, the control sensitivity shall be within the following limits ____________.

3.8 Flying Qualities Requirements for Combined Axes - New Additions

3.8	FLYING QUALITIES REQUIREMENTS FOR COMBINED AXES
3.8.1	Cross-Axis Coupling in Roll Maneuvers. (No revision recommended)
3.8.1.1	RSS cross-axis coupling in roll maneuvers. (New addition)
3.8.1.2	RSS Failure State cross-axis coupling in roll maneuvers. (New addition)
3.8.2 - 3.8.3	(Not considered for revision)
3.8.4	Stalls. (No revision recommended)
3.8.4.1	Stall approach. (No revision recommended)
3.8.4.2	Stall characteristics. (No revision recommended)
3.8.4.2.1	RSS stall characteristics. (New addition)
3.8.4.3	Stall prevention and recovery. (No revision recommended)
3.8.4.3.1	RSS stall prevention and recovery. (New addition)
3.8.5	Departures and spins. (No revision recommended)
3.8.5.1-3.8.5.2	(Not considered for revision)
3.8.5.3	RSS departures and spins. (New addition)
3.8.6	Control Coupling for Failures with RSS. (New addition)

3.8.1.1 RSS cross-axis coupling in roll maneuvers. The special requirements of 3.2.8.6.3 apply in addition to those above (3.8.1), but only for Normal States of the flight control system (pitch augmentation ON, unfailed).

3.8.1.2 RSS Failure State cross-axis coupling in roll maneuvers. With the pitch augmentation function OFF or failed in the flight control system, there is no requirement for pitch-control-fixed rolls. However, the contractor shall define any bank angle and normal acceleration restrictions that apply to rolling maneuvers to avoid dangerous or uncontrolled motions, and these shall ________.

At a minimum, with pilot control of pitch and yaw controls, it shall be possible, without causing any dangerous flight condition or precipitating loss of control, to make bank to bank turn reversals from ± ______ to ∓ ______ degrees in Category C flight phases using the roll control input required to meet Category C Level ______ roll performance requirements of 3.5.9.1.

3.8.4.2.1 RSS stall characteristics. It is desired that the pitching moments break stable at the stall, and remain stable above the stall. However, instability and pitch-up are permitted pr vided the requirements of 3.2.8.6.4 are met.

3.8.4.3.1 RSS stall prevention and recovery. The requirements of 3.8.4.3 apply to aircraft with relaxed static stability, for both Normal and Failure States.

3.8.5.3 RSS departures and spins. The requirements of 3.8.5.1 and 3.8.5.2 apply to aircraft with relaxed static stability, both for Normal States and Failure States (pitch augmentation OFF or failed) of the flight control system, except for aircraft which meet the requirement of 3.2.8.6.4 by virtue of angle of attack limiting. In this latter case the requirements of 3.8.5.1 and 3.8.5.2 need not be met, provided departures from controlled flight are shown to be extremely remote (probability < ________).

3.8.6 Control Coupling for Failures with RSS. For failures of the normal pitch augmentation system (augmentation OFF or failed) for airplanes with relaxed static longitudinal stability, roll control inputs commanded by the pilot or from the augmentation system shall not cause objectionable pitching motions for maneuvers appropriate to the failed condition. Specifically, this applies to bank-to-bank turns from________ to ________degrees of bank angle for Category C flight phases.

SECTION IV

PROPOSED REVISIONS - MIL HANDBOOK

3.1.7.3 RSS Warning and Indication

A. REASON FOR REQUIREMENT

The use of relaxed static stability (RSS) in an airplane poses special requirements on identificaton and annunciation to the pilot of dangerous or potentially dangerous flight conditions. Stability augmentation system failures have exceptional potential for precipitating dangerous conditions, but by observing appropriate restrictions on flight conditions and maneuvers, the pilot will generally be able to avoid these dangerous conditions. Thus it is necessary to insure that the pilot receives adequate warning so that he can take appropriate action.

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.1, 3.4.1.1, 3.4.1.2

C. STATEMENT OF REQUIREMENTS

3.1.7.3 RSS warning and indications. The requirements of 3.1.7.1 apply to conditions of relaxed static stability as identified in 3.1.11 and defined in 3.1.11 of the Handbook, but the requirements of 3.1.7.2 are replaced by the following for warning of dangerous flight conditions resulting from relaxed static stability.

Three levels of warning are required for airplanes with relaxed static stability, as follows.

a. In the event that a flight control system failure will, when followed by a subsequent failure, result in the need for restricting the flight envelope or operation of the airplane to avoid dangerous flight conditions, then a clearly distinguishable warning (a caution) shall be given to the pilot so that he may take corrective action, either to re-establish integrity of the FCS or to restrict flight operations appropriately.

b. In the event that a flight control system failure will result in the need for restricted flight operation of the airplane in order to avoid dangerous flight conditions, then a clearly discernible warning, of a superior nature to that of (a) above, shall be given the pilot so that he may take immediate action.

c. In the event that a flight control system failure will place the airplane in a dangerous flight condition, where structural damage or loss of control is possible, a clearly discernible warning, different from (b) above, shall be given so the pilot can take immediate appropriate action.

Reliability requirements for the above warnings shall be as follows_______________.

The requirements in 3.1.7.2 with respect to functional performance, inadvertent operation, and functional failure shall apply. Nuisance operation shall not be possible for any Level of flying qualities.

D. RECOMMENDATION

Reliability requirements for the three warnings are recommended as follows.

Warning	Probability of Failure
a	$<10^{-2}$ per flight
b	$<10^{-4}$ per flight
c	$<10^{-4}$ per flight

The above failure probabilities are for the warning function alone, and apply if the warning is not given when the failure has occurred, or if the warning is given without the failure actually occurring.

Type (a) failures would have Level 1 flying qualities, or at worst Level 2, and continued normal operation would be possible. Typical of these failures would be a first failure in a three-channel (triplex) redundant FCS, with no noticeable difference in flying qualities detectable to the pilot. A caution is needed because a subsequent failure would require restricted operation to avoid dangerous conditions, and if the subsequent failure were to occur in a prohibited operation, then the results might be catastrophic.

Typically, for an RSS airplane with a triplex system, having had one channel fail, then the second failure could shut down the system leaving the airplane without augmentation. For example, if the pilot was engaged in air combat, and this failure were to occur during an extreme maneuver, departure and loss of control might result. The caution, on the first failure, would then alert the pilot to a potentially dangerous condition, and "tell" the pilot to perhaps break off the engagement. This warning need not be an overriding one, nor necessarily a special one. For the example case, an FCS channel failure light, with accompanying master caution flashing, would serve the purpose.

Type (b) failures would probably be to Level 2 or Level 3 flying qualities, with restrictions imposed on airplane operation, though not necessarily in the flight condition the failure occurred. For the typical example, this failure would be a second FCS failure which shut down the triplex system leaving the pilot with static instability in pitch to deal with. The warning would have to be overriding, perhaps involving a combination of warning lights and aural signals. The warning would immediately "tell" the pilot in the typical example that if he were still engaged in air combat to break off immediately, to avoid any further severe maneuvers such as rapid rolls, and perhaps to go to supersonic speeds in "evacuating" the combat zone in order to leave as rapidly as possible with a statically stable airplane.

Type (c) failures might be to worse than Level 3 flying qualities, at least at some necessary operating condition, with either immediate or subsequent loss of the aircraft possible. The severity of the situation after failure would depend on the aircraft. Typically, for the fighter airplane with triplex system shut down, and with severe control-surface fixed static instability in pitch made controllable at Level 3 flying qualities by an essential SAS, failure of the essential SAS would require a Type (c) warning. If used, the aural warning could be the same as that for Type (b) failures, but the pilot must be able to tell at a glance from the visual warnings that the essential SAS has failed, and that he must observe extreme caution. Appropriate action might be immediate or deferred ejection or evacuation of the aircraft, depending on the specific circumstances the pilot finds himself in. A type (c)

warning is reserved for failure conditions that do not meet the minimum safety requirements, but where the pilot may be able to salvage the situation by exercising extreme caution and taking advantage of every beneficial circumstance possible.

Specific rules for the form of the three types of warning (one a caution) are not defined since they are airplane and mission dependent and need to be integrated with the various other airplane warning systems. However, the pilot should be able to turn off any of the three.

Failure probabilities recommended for the three types of warning systems are the same as those allowed for flying qualities degradation to Level 2 for Type (a) and Level 3 for Types (b) and (c) in the operational flight envelope.

3.1.11 Relaxed Static Stability (RSS)

A. REQUIREMENT

3.1.11 Relaxed static stability (RSS). Special alternate requirements are formulated applicable to the deliberate use of relaxed static stability (RSS). The alternate requirements are formulated on the basis that stability augmentation will be used to provide Normal-State flying qualities.

Quantitative requirements at present are only available for relaxed static stability in pitch, and are found in 3.2 and 3.8.

B. DISCUSSION

The term "Relaxed Static Stability" (RSS) refers to the deliberate design of a statically unstable aircraft (control surfaces fixed) in order to obtain performance or other benefits. The static instability referred to will generally be most severe in some flight conditions, and may require flight control stability augmentation to meet failure state flying qualities requirements (3.1.6) as well as normal state requirements (3.1.5). Stability augmentation may be required even to meet minimum Level 3 failure state requirements. This approach is at direct variance with much of the expressed intent of this flying

qualities specification, for example 3.1.7.2, and necessitates the treatment of relaxed static stability as a special case with special qualitative and quantitative requirements.

There is a certain amount of risk assumed in the use of RSS, particularly when reliance is placed on the flight control augmentation for flight safety, so the performance benefits should certainly be examined critically to ensure that they are worth the risk. However, such risks have been taken in the past, for example in the use of hydraulic power alone for control surface actuators without mechanical reversion, and in time the use of RSS will fit into the design process and specifications as a normal procedure.

There are generally two forms that relaxed static stability can take, longitudinal stability and directional stability. Relaxed static longtudinal stability is generally implemented by positioning the center of gravity aft of that normally required for stability. The result is a positive or unstable value for the gradient of pitching moment with angle of attack (C_{m_α}), which in turn means that as angle of attack increases, a nose down control moment is required to balance the airplane. For a conventional configuration the net result is an up-load on the tail which increases lift efficiency and decreases drag, especially trim drag. The horizontal tail, now sized for control power, can generally be smaller. Fuselages and landing gear can be shortened, and significant weight savings realized. The benefits in cruise efficiency and maneuver capability, though most significant for supersonic aircraft, are still important for subsonic ones. Estimates of reductions in fuel consumption in cruise range from 10 to 15%. For aircraft to have sustained supersonic capability, relaxed static stability is generally recognized as a necessity. Kehrer (Ref. 14, 15 and 16) gives an excellent description of the benefits and technical problems associated with the use of RSS for both supersonic transport and tactical aircraft.

Longitudinal static instability can be caused by a negative pitching moment gradient with airspeed (negative M_u), which can result from power or thrust effects, aerolasticity, or transonic aerodynamic characteristics. Instability due to M_u has primarily to do with speed change and acts quite differently from instability due to $M\alpha$ which

affects primarily the short period and attitude response. Any significant M_u, positive or negative, is generally undesirable. A detailed comparison of the two types of instability is found in Appendix B, Section B.1.2. It suffices to state here that, though M_u does affect stability and attitude response and these effects must be accounted for in any RSS criteria, the specific M_u type instability is not considered to be "relaxed static stability (RSS)" as defined here.

Specifically, relaxed static stability in pitch is defined as placing the center of gravity aft of the c.g. range normally chosen to assure good or acceptable longitudinal stability and response. Alternatively for tailed airplanes, relaxed static stability in pitch can be taken to mean a configuration in which the horizontal tail is not large enough to meet the MIL-F-8785C requirement (3.2.2.1.1) on ω_n^2/n_α (Ref. 13). A definition similar to the latter holds for relaxed static directional stability.

The use of relaxed static directional stability, to the extent of instability, has not received much attention. In the late 1950's a number of fighter and research aircraft (F-100, F-101, F-102, F-104, X-2, and X-5) ran into serious difficulty, with aircraft lost, because too low directional stability precipitated divergence and loss of control in rolls due to roll coupling. Recently, interest has been shown in eliminating the vertical tail in order to reduce radar cross-section for aircraft which must penetrate enemy defenses. The general requirements for the use of directional RSS are the same as those for longitudinal RSS, but the detail requirements are quite different with a negligible amount of data available to support the formulation of such requirements. Accordingly, the formulation of detailed requirements for RSS is restricted to the longitudinal case.

The requirements for relaxed static stability are formulated as separately identified individual requirements, either in addition to or replacing existing specification requirements. The object is to allow the contractor to decide, based on the results of design studies, whether the risk of incorporating RSS in the design is worth the benefits. On the other hand, the procuring agency is given the option of vetoing the use of RSS by its selection of flying qualities Levels and reliability requirements for failure states of the flight control system (3.1.11.2.2).

It should be noted that at issue here is not whether the requirements for stability can be relaxed some, allowing augmentation to make up the deficiency. This level of relaxation has long been a fact, ever since augmentation was allowed to be used in meeting any of the requirements. Also not at issue is the acceptance of static instability, since static spiral instability is presently allowed (3.3.1.3 of MIL-F-8785C). What is at issue is whether a significant level of static instability is to be allowed, and more specifically, whether total failure of the flight control augmentation system is to be allowed to degenerate flying qualities to worse than Level 3, or in other words, whether it is acceptable to consider an augmentation system as flight critical and necessary for flight safety.

Clearly, given conditions involving RSS, any failure mode analysis must be conducted on a probabilistic basis where failure states of the augmentation system are involved. A purely generic analysis or approach as defined in 3.1.6.2 has little to offer, as it can only legislate the minimum number of redundant or dissimilar channels, or against the use of RSS at all.

An important aspect of the use of RSS is that the approach and landing task will generally be critical. This criticality is due to the low Mach number, low dynamic pressure, high lift coefficient, and high probability of encountering turbulence. There is no way to avoid this critical task - the airplane must be landed.

3.1.11.1 RSS Normal-State Flying Qualities

A. REASON FOR REQUIREMENT

One purpose of this paragraph is to specifically point out that aircraft with relaxed static stability (RSS) are expected to meet all the requirements that inherently stable aircraft have to meet. This applies as long as the flight control system is operating in its normal state, that is, with stability augmentation providing the stability which the aircraft, with control surfaces fixed, inherently lacks. This stability augmentation system is termed the RSSAS (Relaxed Static Stability Augmentation System). The other purpose, even more important, is to

emphasize that aircraft with RSS must meet additional requirements on control power (authority and rate), and on high angles of attack characteristics that airplanes with inherent stability do not have to meet.

B. RELATED MIL-F-8785C REQUIREMENTS

3.1.10, 3.1.10.1, 3.1.10.3.1, 3.1.10.3.3

C. STATEMENT OF REQUIREMENT

3.1.11.1 RSS Normal-State flying qualities. The Levels of flying qualities as specified in 3.1.5 apply to airplanes with relaxed static stability for the aircraft operating in a normal, unfailed state. Special requirements on control power (3.2.8), control forces (3.2.9), control displacements (3.2.10), and control coupling and flight at high angles of attack (3.8) must be met in addition.

D. DISCUSSION

The approach taken, in developing the statement of the special requirements for the use of RSS, is to explicitly call out in each requirement subparagraph the other related requirements of the major paragraph that must be met for normal states of the flight control system. Then any additional requirements that must be met are stated. In some cases, the requirements for failure states follow; in others, the failure state reqirements are stated in a separate numbered subparagraph.

3.1.11.2 RSS Failure-State Flying Qualities

A. REASCN FOR REQUIREMENT

It is necessary to distinguish between Failure States where the normal requirements apply and those where the requirements are modified for an RSS airplane. This paragraph identifies the two categories of failures and then specifies the application of Flying Qualities Levels and other requirements by subparagraph.

B. STATEMENT OF REQUIREMENT

3.1.11.2 RSS Failure-State flying qualities. Two categories of Failure States are defined for aircraft with relaxed static stability, those States where the failures do not involve or affect the components of the flight control augmentation system which augments the relaxed static stability, and those failures which do involve or affect such components. Requirement 3.1.11.2.1 applies to the former, requirement 3.1.11.2.2 to the latter.

C. DISCUSSION

Two categories of failures are defined in this paragraph, those failures which do not affect the RSS augmentation and those that do. By RSS augmentation system (RSSAS) is meant any part of the flight control system which is needed to stabilize in normal operation the inherent control-surface-fixed instability associated with RSS. Subparagraphs 3.1.11.2.1 and 3.1.11.2.2 then list the specific requirements for each category.

The intent is to maintain unchanged the failure state requirements unrelated to relaxed static stability, but to modify the failure state requirements that are related to relaxed static stability to enable its use to the extent desired or allowed by the procuring agency.

The use of RSS clearly requires that stability augmentation be used to provide satisfactory flying qualities. Furthermore, the prohibition of dangerous or intolerable flying qualities due to a single failure

(3.4.9, MIL-F-8785C) means that redundancy of RSS augmentation is required if control-surface-fixed instability is sufficiently severe. Even without this single failure requirement, it is anticipated that multiple redundancy and/or dissimlar redundancy will be used to achieve the required mission reliability and flight safety.

The following two functions and their characteristics are generally envisioned for RSS augmentation (RSSAS) in the flight control system (FCS).

Normal FCS. Multiply redundant. Meets mission reliability requirements, mission critical. Meets normal flying qualities requirements, meets reliability requirements for operational and service envelopes. May meet flight safety requirements for RSS, in which case it provides the essential FCS function.

Essential FCS. Multiply redundant. Meets flight safety requirements for RSS, flight safety critical. Required as back-up to normal FCS, where normal FCS does not meet flight safety requirements.

The essential FCS will generally emphasize simplicity, may have high levels of redundancy, will generally provide dissimilar redundancy when compared to the normal FCS, and will require highly reliable power sources including independent emergency sources.

Continual reference is made to "failure of the flight control augmentation system that stabilizes an inherently (control surface fixed) unstable airplane", or "failure states (pitch augmentation OFF or failed) of the flight control system." This refers to either failures of the augmentation system, or the deliberate turning OFF of part or all of the augmentation system which stabilizes or modifies the stability, or guards against the instability, of an airplane with inherent or control-surface fixed relaxed static stability of a severe nature. Severe relaxed static stability certainly includes any degree of relaxed static stability that has Level 3 or worse flying qualities, whether the airplane is unstable

or has a low level of stability. Relaxed static stability refers to any case of static instability (spiral mode instability excepted) even though it has Level 2 flying qualities. In the strict sense, relaxed static stability means any level of static stability that does not meet the normal specification requirements and requires augmentation to do so.

For the purposes of this specification, relaxed static stability is defined as any condition for which the contractor elects to use the alternate requirements for "relaxed static stability" instead of the normal ones they replace. In this case, the contractor must use all those requirements applicable to a particular type of relaxed static stability (longitudinal or directional) and may not pick and choose which ones to meet. The need for electing a group or package is because some of the requirements, notably on control authority, rate, and reliability, are more stringent than the normal requirements.

As presently formulated, almost all the special quantitative requirements for relaxed static stability refer to static longitudinal stability and the pitch augmentation system (PAS). As a practical rule of thumb, any airplane can be considered a candidate for relaxed static stability that does not meet in landing approach the MIL-F-8785C Level 2 requirements for short period frequency (3.2.2.2, MIL-F-8785C) in Category C flight phases.

The RSSAS requirements refer to applicable FCS failure states as augmentation OFF or failed. Failure cases refer to the normal FCS, where the failure has led to a degradation of stability, by a failure of one or more channels. If the failure of a single channel in a multiple redundant system does not lead to a degradation of stability or flying qualities, and operation can continue normally, then the RSSAS is not considered to have failed. If a subsequent failure can lead to flying qualities that do not meet the normal requirements, are dangerous, and require restricted flight operation, then warning of this condition is required (3.1.7.3).

Since the FCS may have several levels of failure, with effects on RSSAS ranging from none to complete loss, and involving just the normal FCS or both normal and essential FCS, a complete Level structure with

associated requirements and allowable failure probabilities is provided (3.1.11.2.2). This structure only becomes applicable under failure states which directly affect the RSSAS.

The first effect of RSSAS failures is found as a requirement for a warning (3.1.7.3) of an impending effect on RSSAS with one additional failure, though no effect has yet been evidenced by previous failures. Evidence of an effect is defined as a degradation in Level, e.g., from Level 1 to 2 in the operational envelope.

The next degree of effect occurs when an FCS failure actually does cause degradation of flying qualities from normal state flying qualities, evidenced by a degradation in Level, to Level 2 or 3. At this point, the relaxed requirements for RSS take effect and allow less static stability than the normal requirements, but safeguarded by the new reqirements applicable to RSS. At this point, the aircraft may have no pitch augmentation, or it may be relying on the essential FCS augmentation which may be either a separate, highly reliable system or the final level(s) of a multiply redundant system.

The final effect of RSSAS failures is treated in 3.1.11.2.2 where failures to worse than Level 3 are considered. If the failure to worse than Level 3 is prohibited, then no essential RSSAS is needed since Level 3 is defined as safe to get home and land. If the failure to worse than Level 3 is not prohibited, then the essential RSSAS protecting against this worse than Level 3 instability must have high reliabiity, defined in 3.1.11.2.2. Since its operation is critical to flight safety, the reliability of the essential FCS must be on the order of structural integrity, and the probabilty of failure must be less than the probability of aircraft loss per flight due to FCS failures as given in 3.1.7 of MIL-F-9490D.

The RSSAS requirements refer to an augmentation OFF condition. This condition assumes that some or all of the augmentation for RSS can be turned off, but presumably not essential FCS augmentation that is required for flight safety. Three logical reasons for switching OFF the normal augmentation (essential FCS excluded) can be readily envisioned:

1) to demonstrate compliance with failure requirements
2) to identify and correct failures
3) for training and proficiency in failure state operation

The essential FCS augmentation must not be turned off in RSS critical conditions, and the requirement of 3.1.11.2.2 effectively prohibits giving the pilot the ability to switch OFF this essential augmentation function without specifically prohibiting switches.

3.1.11.2.1 Failure-State Flying Qualities - RSS Augmentation Not Affected

A. REASON FOR REQUIREMENT

For failures that do not impair the operation of the relaxed static stability augmentation function of the FCS, there is no reason for relaxing the failure state requirements. This requirement is needed in order to prevent application of the relaxed requirements when not warranted.

B. STATEMENT OF REQUIREMENT

3.1.11.2.1 Failure-State flying qualities - RSS augmentation not affected. For these Failure States, the Level of flying qualities shall be as specified in 3.1.6.

3.1.11.2.2 Failure-State Flying Qualities - RSS Augmentation Affected

A. REASON FOR THIS REQUIREMENT

This requirement establishes the lowest level of flying qualities allowable for failure states and the corresponding reliability requirements where the failures are material to the relaxed static stability augmentation system (RSSAS).

B. RELATED MIL-F-8785C REQUIREMENT

3.1.10.2, 2.8.3.2

C. STATEMENT OF THE REQUIREMENT

3.1.11.2.2 Failure-State flying qualities - RSS augmentation affected. For these Failures States which involve failure of the flight control augmentation system that stabilizes an inherently unstable airplane, the method of 3.1.6.1 applies, but the following changes and additions are made.

Failures of the flight control augmentation system can degrade flying qualities to worse than Level 3, and such types of failures are______.

D. RECOMMENDATION

The procurement agency has basically two choices: 1) prohibit worse than Level 3, and 2) allow worse than Level 3 with appropriate safety requirements. The two optional recommendations follow.

Prohibit Worse than Level 3

not allowed, except as a Special Failure State.

Allow Worse than Level 3

allowed, if their probability is sufficiently small as defined in the following and by Table 1.

The contractor, in addition to the calculations of 3.1.6.1, shall calculate by the method of 3.1.6.1 the overall probability per flight that flying qualities will degrade below Level 3 due to all failure states which involve failures material to the augmentation of relaxed static stability. These probabilities shall be less than the probabilities specified in Table 1.

If the FCS has an essential FCS augmentation function, as defined in 3.1.11.2 of the Handbook, which prevents worse than Level 3 flying qualities due to RSS, then the pilot should be given no means for eliminating this function in conditions where it is critical to flight safety. If (to enable repair, testing, etc.) the pilot or other crew member is given this ability, e.g., through an ON-OFF switch or a switching sequence, then protection must be provided against the pilot

eliminating the essential FCS augmentation function in conditions where its use is critical. The reliability of the ON-OFF mechanism and the protective device must be included in the above probability calculations.

Table 1 (3.1.11.2.2). Allowable Probabilities of Encountering Worse Than Level 3 Flying Qualities Due to Relaxed Static Stability

PROBABILITY OF ENCOUNTERING	WITHIN OPERATIONAL FLIGHT ENVELOPE	WITHIN SERVICE FLIGHT ENVELOPE	WITHIN PERMISSIBLE FLIGHT ENVELOPE
Worse than Level 3 after failure	< _____ per flight	< _____ per flight	< _____ per flight

A degradation in flying qualities is allowed with increasing turbulence. Table 2 specifies the Level requirements as a function of turbulence level, flight phase category, flight envelope, and the probability of encountering the degradation due to failure of RSS augmentation. These requirements in Table 2 are to be used instead of, and supersede, the requirements of 3.1.6.1, or 4.4 (3.8.3.2 of MIL-F-8785C) for failures material to relaxed static stability augmentation.

Table 2 (__) (3.1.11.2.2). Levels for Airplane Failure States with Relaxed Static Stability for _____ Turbulence in Category _____ Flight Phases

PROBABILITY OF ENCOUNTERING PER FLIGHT	WITHIN OPERATIONAL FLIGHT ENVELOPE	WITHIN SERVICE FLIGHT ENVELOPE	WITHIN PERMISSIBLE FLIGHT ENVELOPE
Level 2			
Level 3			
Worse than Level 3			

Recommended Values for Table 1 and 2

The probabilities of encountering worse than Level 3 flying qualities, the values to be inserted in Table 1, are equated to the probability of aircraft loss due to flight control failures from the flight safety requirements (3.1.7) of MIL-F-9490D.

$$Q_{s(fq)} = (1 - R_s)\, A_{s(fq)}$$

$Q_{s(fq)}$ - maximum allowable probability of flying qualities worse than Level 3, equal to aircraft loss rate due to failures affecting flying qualities

$A_{s(fq)}$ - flight safety allocation factor for flying qualities, equal to flight safety allocation factor for flight controls (chosen by contractor)

R_s - overall flight safety requirement (specified by procuring agency)

If the overall flight safety requirement is not specified, then the values in Table 3 should apply.

Table 3 (3.1.11.2.2). Quantitative Flight Safety Requirements for Flying Qualities

CLASS AIRCRAFT	SAFETY REQUIREMENTS (NO R_S SPECIFIED)
III	$Q_{S(fq)} \leq 5 \times 10^{-7}$
I, II, IV	$Q_{S(fq)} \leq 100 \times 10^{-7}$

The values of $Q_{s(fq)}$ for RSS augmentation failures (all FCS failures if any others are allowed to degrade flying qualities to worse than level 3) apply to the whole flight envelope: operational, service, and permissible.

The recommended values of the probabilities of encountering flying qualities degradation with failure states, for insertion in Table 2, are found in Tables 4 and 5. No degradation in flying qualities is allowed

with turbulence level until it exceeds moderate, and all flight phases are combined, so only two tables are needed. The probabilities must be consistent with the values in Table 1 of 3.1.6.1 (Table III, 3.1.10.2 of MIL-F-8785C) and Table 1 (3.1.11.2.2).

Table 4 (3.1.11.2.2). Recommended Values for Table 2(a)
Calm to Moderate Turbulence
Category A, B, and C Flight Phases

PROBABILITY OF ENCOUNTERING PER FLIGHT	WITHIN OPERATIONAL FLIGHT ENVELOPE	WITHIN SERVICE FLIGHT ENVELOPE	WITHIN PERMISSIBLE FLIGHT ENVELOPE
Level 2	$< 10^{-2}$		
Level 3	$< 10^{-4}$	$< 10^{-2}$	
Worse than Level 3	$< Q_{S(fq)}$	$< Q_{S(fq)}$	$< Q_{S(fq)}$

Table 5 (3.1.11.2.2). Recommended Values for Table 2 (b)
Moderate to Severe Turbulence
Category A, B, and C Flight Phases

PROBABILITY OF ENCOUNTERING PER FLIGHT	WITHIN OPERATIONAL FLIGHT ENVELOPE	WITHIN SERVICE FLIGHT ENVELOPE	WITHIN PERMISSIBLE FLIGHT ENVELOPE
Level 2			
Level 3	$< 10^{-2}$		
Worse than Level 3	$< 100\ Q_{S(fq)}$	$< 100\ Q_{S(fq)}$	$< 100\ Q_{S(fq)}$

Application of Levels as a Function of Turbulence Intensity

The definition of Flying Qualities Levels to be used in the probability calculations for Table 1, also Table 1 (3.1.6.1), should for the quantitative requirements use the turbulence intensity appropriate to the

specified airplane mission and flight phase. The range of turbulence intensity in Table 2 for which no degradation in flying qualities is permitted should also correspond to the same intensities. Where quantitative requirements are not specified as a function of turbulence intensity, some normal or average intensity is implicitly assumed, usually light to moderate as defined by the data on which the requirements are based. On this basis, the recommended probability values in Table 4 for use in Table 2(a) allow degradation only for turbulence intensities in excess of moderate.

The definition of Flying Qualities Levels for use in the probability calculations for Table 2 depends on having a defined gradation in flying qualities with turbulence intensity for the various Airplane Failure States. This definition will normally come from pilot evaluations in ground simulators, though for RSS pitch attitude response in landing (3.2.1.3) this definition is provided by the specification requirement. If Levels for Airplane Failure States (Table 2) have different probability requirements for different flight phases or categories (e.g., separate Table 2 for Category C phases and Category A and B phases), then separate probability calculations must be made to determine which is critical.

Where the definition of Flying Qualities Level is based on pilot evaluations in simulation or flight test using the Cooper-Harper rating scale, the following equivalence between Level and pilot rating is recommended for all Category A, B, and C flight phases except landing.

Level	Pilot Rating
1	≤ 3.5
2	$3.5 < PR \leq 6.5$
3	$6.5 < PR \leq 9.5$
>3	>9.5

For landing the Level 3 boundary is made more stringent as follows.

Level	Pilot Rating
3	$6.5 < PR \leq 8.5$
>3	>8.5

The more stringent Level 3 boundaries could well be applied to any flight phases that must be completed safely for the airplane and pilot to survive without damage or injury (e.g., cruise, descent, wave-off/go-around.)

E. RATIONALE BEHIND REQUIREMENT

The requirement is formulated so that the procurement agency can either prohibit or allow worse than Level 3 flying qualities in the event of an augmentation system failure. If such failure states are prohibited, then the failure state requirements of MIL-F-8785C can be applied without modification to the relaxed static stability. However, if worse than Level 3 flying qualities is allowed, then a new set of requirements is needed relating system reliability, allowable Levels of flying qualities, and degradation of flying qualities with turbulence. The remainder of this discussion concerns only the latter option and the new requirements.

Flight Safety Reliability Requirement

The first part of the requirement, summarized in Table 1, simply adds a third row (worse than Level 3) and third column (permissible flight envelope) to Table 1 of 3.1.6.1 (Table III, 3.1.10.2 of MIL-F-8785C). Though MIL-F-8785C does not permit worse than Level 3 (except as a Special Failure State), MIL-F-9490D recognizes this rather obvious possibility and places reliability limits on its occurrence as a flight safety requirement, 3.1.7. This flight safety requirement ($Q_{s(fc)}$) has been interpreted as a flying qualities flight safety requirement ($Q_{s(fq)}$), and the allowable aircraft loss rates due to FCS failures from MIL-F-9490D used directly for the allowable probabilities of worse than Level 3 flying qualities due to FCS failures and relaxed static stability. Implicit in this requirement is the assumption that worse than Level 3 flying qualities is unsafe and tantamount to loss of the aircraft.

The requirements of Table 1 extend the application of Levels to the permissible flight envelope for relaxed static stability requirements for very solid reasons. If, for example, an airplane with relaxed static

stability is flying outside the service envelope in normal state, and an augmentation failure occurs which would produce Level 3 in the operational or service envelope, then the airplane would probably become uncontrollable and would be lost if stability were any worse in the permissible flight envelope outside the other envelopes. To protect against this circumstance, Level 3 flying qualities are ensured by requiring flight safety reliability in the permissible flight envelope as well as the operational and service envelopes.

In considering, or selecting, failure state requirements for relaxed static stability, it must be remembered that the effect of latent as well as realized failures must be protected against. If a failure occurs that does not degrade flying qualities, but a second subsequent failure would degrade flying qualities below safe levels, then probability of the second failure must be remote ($<Q_{s(fq)}$), or the flight envelope must be restricted to conditions safe for the second failure.

Safeguards for Essential FCS Functions

The second part of the requirement essentially prohibits giving the pilot a switch to turn off an essential FCS function, e.g., RSS augmentation which if turned off would result in worse than Level 3 flying qualities. However, there may be valid reasons for being able to turn off this essential FCS, for testing or repairs, when an alternate system can provide the essential function, or in a flight condition where this function is not flight safety critical. Accordingly, the wording of the requirement is intended to allow this ability, to turn off the essential FCS, with appropriate safeguards. However, on the basis that the essential FCS is required for flight safety, and pilot errors do occur, it would be entirely reasonable to prohibit giving the pilot any means for turning off the essential FCS.

Failure State Requirements as a Function of Turbulence

The third part of the requirement defines the degradation in failure state flying qualities that is allowed with increasing intensity of turbulence, or atmospheric disturbance. These requirements relate to 3.8.3 of MIL-F-8785C and 4.3 and 4.4 of the proposed MIL Handbook (Ref. 18). Flying qualities Level can be defined or specified in at least

three different ways, by quantitative specification requirements, by qualitative specification requirements, or by pilot rating. Most quantitative requirements specify Level as a function of measurable airplane characteristics or parameters, with some nominal or average intensity of turbulence implicitly assumed in the requirement. For these, Level is fixed by the airplane parameters and does not change no matter how severe the turbulence. Some requirements specify Level as an explicit function of turbulence as well as airplane parameters. This approach was chosen for the requirements for RSS pitch attitude response (3.2.1.3) because of the dominant influence of turbulence intensity. For these latter, since pilot rating generally degrades with turbulence, the requirments for a given Level will generally become more stringent as turbulence increases (e.g., 3.2.1.3).

Most individual qualitative requirements, on the other hand, state a quality or condition (or absence thereof) that should exist, often without reference to Level of flying qualities or to quantitative measures. However, there are also the general requirements of 3.1.5 and 3.1.6 (3.1.10 of MIL-F-8785C) prescribing the Levels for Airplane Normal States and the allowable probabilities for degraded Levels for Airplane Failure States. Assessment of compliance becomes a matter of judgement, often depending on pilot evaluations in simulators or flight test. Since turbulence generally adds to pilot work load, failure to meet these requirements is more likely for higher intensities of turbulence.

Flying qualities, as defined by pilot rating in simulators or flight test using the Cooper-Harper rating scale, will generally degrade with increasing turbulence for a given airplane and mission task. With a fixed relationship between pilot rating and Level of flying qualities, the Level as defined by pilot rating will thus degrade with increasing turbulence for a given airplane and piloting task.

Failures and turbulence can both be characterized as random events. Both are unlikely events, failures by design and high turbulence intensities by nature. The intent is to appropriately relax the requirements for the simultaneous occurence of failures and high intensity turbulence so as to avoid forcing unwarranted design compromises to meet the more unlikely combined events.

The approach taken in MIL-F-8785C (3.8) is to use a dual definition of flying qualities, defined by quantitative Level requirements as one metric of flying qualities, and defined by "qualitative degrees of suitability" as a second metric using the Cooper-Harper scale primary adjectives of "Satisfactory", "Acceptable" and "Controllable", plus a fourth "Recoverable". Definitions of the first three words use precisely the word definitions of Levels 1, 2 and 3. Recoverable is defined as good enough control to fly out of a disturbance during landing (or any other flight phase) and to perform a wave-off/go-around (landable only with improved conditions). Flying qualities for both Normal and Failure States as defined by Level are not allowed to degrade with increasing turbulence, except for turbulence in excess of moderate where no quantitative Level requirements are imposed. Flying qualities as defined by "qualitative degrees of suitability" are allowed to degrade with increasing turbulence. For Failure States the problem of formulating a four dimensional requirement (flying qualities, turbulence, flight envelope, and probabilities) is solved by defining Failure States I and II to be the two row vectors of probabilities from Table III (3.1.10.2 of MIL-F-8785C), thus eliminating flight envelope from the failure state matrix (Table XVII, 3.8.3.2 of MIL-F-8785C). The approach has commendable features and should be easy to use, but also deficiencies. The primary one is that it fails to address the probabalistic problem of combined failures and turbulence from a probabilistic viewpoint. Degradation with turbulence intensity is in whole Level increments (as defined by the degrees of suitability) regardless of the flight phase or the probability of encountering the turbulence.

The proposed MIL Standard and Handbook of Hoh, et al. (Ref. 17 and 18) offer a somewhat different approach. These define Flying Qualities Level separate from quantitative requirements by either of two options, (1) Cooper-Harper pilot rating, or (2) by the "words" describing the qualitative degrees of suitability of MIL-F-8785C. For Normal States, when Level is defined by pilot rating, a sliding scale of pilot rating is proposed with turbulence intensity, except "recoverable" is used as a first tier below PR = 9.5. When the second or "word" definition of Level is used, the results are the same as MIL-F-8785C for Normal State flying qualities (Table XVI, 3.8.3.1). For Failure State flying qualities the

results are similar in form to those of MIL-F-8785C, but the failure state matrix identifies simply the required Levels, which in themselves degrade with turbulence intensity according to whichever definition is used. Though the pilot rating definition of Level allows a gradual and flexible degradation of flying qualities with turbulence, it fails to address the probabalistic problem of combined failures and turbulence in a probabilistic manner. However, the Carlson (Ref. 20) approach, including his figure showing the application of combined turbulence and failure effect probabilities to Level definition, is recommended for guidance (Ref. 18, 3.1.6.1, F).

The approach recommended here for RSS failures attempts to modify the approach of MIL-F-8785C so that it allows for (1) quantitative requirements which have Level Boundaries defined as a function of the turbulence intensity, (2) a probabalistic treatment of combined failure effects and turbulence intensity, (3) the degradation in flying qualities due to failures to vary as a function of the probability of encountering the various turbulence intensities so that some net probability of a given Level will be realized, and (4) flexibility so the probability requirements may be tailored to the specific application, including varying turbulence intensities and probability of encounter as a function of mission flight phase. A discrete approach, like that of MIL-F-8785C, is recommended as one option. A second option is also recommended which uses the continuous approach of Carlson (Ref. 20).

Basic to the specification of flying qualities criteria for Airplane Failure States, also Normal States, is the selection or definition of the design turbulence environment. This is the most severe environment the airplane will be expected to encounter normally, and for which no degradation in flying qualities will be allowed. This design environment establishes the format of Table 2, that is, its lowest range of turbulence intensities as a function of flight phase and category. It should also be the turbulence environment used to calculate the probabilities relative to Table 1 (3.1.6.1) and Table 1 (3.1.11.2). Table 2 essentially replaces Table XVII, 3.8.3.2 of MIL-F-8785C, but adds the failure state probability conditions from Table 1. This set of conditions (Table 1) could have been designated as Failure State III, and a third column added to Table XVII. However, the degradation with

turbulence using the format of Table XVII must be in whole Level increments, and allows no variation with flight phase. The formulation of Table 2 is more flexible. It allows different requirements for different flight phases. The reduction in probability of a given Level of flying qualities with increasing turbulence can be made gradual, and not just a shifting of whole Level values, and directly related to the combined probabilities of selected turbulence intensities and reduced Levels due to failures.

The recommended values in Tables 4 and 5 for insertion in Table 2, part (a) and (b), are based on allowing degradation in flying qualities only for turbulence intensities in excess of moderate for all flight phases, and reflect the understanding that most quantitative requirements are based on data which included moderate turbulence in the evaluation tasks. The probability values in Table 4 are just those from Table 1 (3.1.6) and Table 3. Since the probability of severe turbulence is 10^{-2} less likely than moderate turbulence (see Table 6), the values in Table 4 have been reduced by this amount to produce Table 5. Since the probability of exceeding moderate turbulence is $< 10^{-3}$ (Table 6), the combined probability of worse than Level 3 in moderate to severe turbulence is still $< 0.1Q_{s(fq)}$.

Table 6 (3.1.11.2.2). Discrete Turbulence Levels, Exceedence, and Intensity

TURBULENCE LEVEL	EXCEEDANCE PROBABILITY		VERTICAL GUST INTENSITY	
	MEDIUM/HIGH ALTITUDE	LOW ALTITUDE	$\sigma_{\omega 5000}$ FT FT/SEC	$\sigma_{\omega 20}$ FT FT/SEC
Light	10^{-2}	10^{-1}	5	2.5
Moderate	10^{-3}	10^{-3}	10	5.1
Severe	10^{-5}	10^{-5}	22.5	7.6

Note: $\sigma_u = \sigma_v = \sigma_w$ at 5000 feet

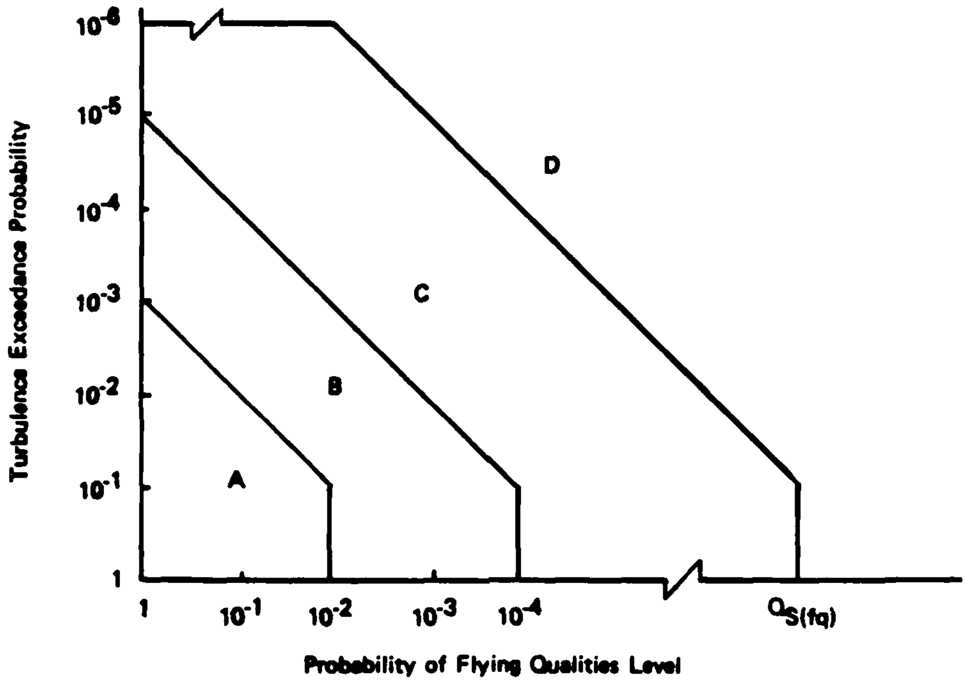
$\sigma_u = \sigma_v = 1.93\sigma_w$ at 20 feet

The allowable degradations in flying qualities, defined by the probability requirements in Table 2 (following the precedent of Tables XVI and XVII of MIL-F-8785C, 3.8.3), are for discrete ranges of turbulence intensity. Turbulence effects are generally stated for discrete intensities, and the intensities from the turbulence model of 4.1 (3.7 of MIL-F-8785C) are listed in Table 6 together with approximate exceedence probabilities and rms intensities at key altitudes. These discrete intensities, including the appropriate variation of characteristics as defined in the turbulence model of 4.1, are the levels to be used in characterizing the ranges of Tables 4 and 5 (also Tables XVI and XVII, 3.8.3 of MIL-F-8785C). The appropriate turbulence effect for each range will normally be for the highest level of turbulence in the range to cover the worst case.

An alternative set of requirements for the probability of encountering Levels of flying qualities in turbulence, replacing Table 2, is a rational approach based on the Carlson (Ref. 20) recommendation for requirements based on the combined probabilities of turbulence and failure states. Figure 1 shows the requirement applied using 10^{-1} times the basic (calm air) failure state probability for the combined probability. No requirement (> 3, worse than Level 3) is shown for turbulence above an exceedence of 10^{-6}. The primary effect of the relaxed static stability shows up in that Level 3 or better flying qualities are required throughout Region A, B, and C in Figure 1. This approach recognizes that the probability of encountering severe levels of turbulence and hazardous failure states simultaneous is extremely remote, and airplane design should not be compromised to meet such conditions.

Application of Levels in Turbulence

The fourth part of the requirement treats the definition of flying qualities Levels and how they relate to airplane parameters and pilot rating. The definition of Level 3 in terms of pilot rating (PR = 6.5 to 8.5) for the landing is not the usual one, and the reasons for raising the lower boundary from the commonly accepted 9.5 to the recommended 8.5 are described in detail in 3.2.1.3 (RATIONALE, subparagraph on Parametric Criterion). Briefly, the definition of Level 3 (e.g., 1.5 of MIL-F-8785C) states," -- Category B and C Flight Phases can be com-



FLIGHT ENVELOPE	LEVELS OF FLYING QUALITIES			
	A	B	C	D
Operational	1	2	3	>3
Service	2	3	3	>3
Permissible	3	3	3	>3

Figure 1 (3.1.11.2.2). Flying Qualities Requirements for Failures with Relaxed Static Stability in Turbulence

pleted." The definition implies "safely", and is so interpreted. Since a PR = 9 requires maximum pilot effort to avoid loss of control, hence allows no margin for error, a landing made at this ragged edge of control would not appear to be safe -- and the airplane must be landed! Similarly, some Category B flight phases such as cruise and descent must be completed safely in order to land the airplane safely. The same PR = 8.5 boundary might well apply to these rather undemanding but still vitally necessary mission tasks. In other words, this more stringent Level 3 boundary should apply to any flight phase which is the last resort when other more demanding flight phases or tasks are aborted.

F. GUIDANCE FOR APPLICATION

Application of the Level concept for relaxed static stability follows very much the procedures outlined in 3.1.6.1. The major differences are that Level 3 flying qualities are required in the permissible flight envelope, and reliability and failure effect analyses must be conducted in the permissible flight envelope with regard to flight safety and the effects of relaxed static stability.

The use of piloted simulation takes on added importance in defining Level 3 or safe flying qualities following failures material to relaxed static stability augmentation. Flight phases and flight envelopes must be examined carefully to assess restrictions that may need to be imposed as a result of failure states and dangerous latent or potential failure states and conditions.

Basic to the specification of flying qualities for Airplane Failure States, also Normal States, is the selection or definition of a design turbulence environment. The design environment is the most severe turbulence that the airplane will normally encounter in performing its intended mission. More directly, it is the turbulence environment for which the airplane should be designed to meet the flying qualities requirements (Table 1 (3.1.5), Table 1 (3.1.6.1), Table 1 (3.1.11.2.2)), and for which there should be no allowed degradation in flying qualities due to turbulence. Where quantitative requirements give Level as a function of turbulence, the design turbulence intensity should be used to define the applicable quantitative requirements. Where quantitative

requirements are not given as a function of turbulence, as is mostly the case, if the specified environment is unusual, it might be worthwhile to examine the background data to see if a change in the Level boundaries is appropriate.

Degradation of flying qualities with increased turbulence intensity above the design turbulence environment is allowed to avoid forcing unwarranted design requirements, complexity, and compromises. This degradation will generally occur for any airplane, except one with "perfect gust alleviation". The intent is that the design turbulence environment be the critical condition. However, the flying qualities degradation experienced by a given airplane depends on its sensitivity to turbulence which, in turn, depends on the airplane characteristics, state, and flight control system sensor and augmentation system design including active control functions.

For Normal State flying qualities, the allowed degradation with turbulence as specified in MIL-F-8785C (3.8.3.1) or in Reference 18 (4,3) is intuitively or arbitrarily based, albeit on significant experience, which may not be a bad basis. On the other hand, since requirements for flying qualities failures and mission reliability and flight safety all have a probabilistic basis, with some evidence from experience with service aircraft supporting their validity, it would appear that flying qualities degradation due to turbulence (itself described by probabilities) should have a similar basis. In fact, the probabilities of flying qualities degradation due to failures and turbulence ought not to be too different.

Failure State flying qualities requirements as a function of turbulence intensity have been formulated here (3.1.11.2.2) on the above basis for relaxed static stability. Recommended values of probabilities for failure state requirements are based on maintaining a constant probability of a given Level of flying qualities under combined failures and turbulence encounters. The values are also based on the presumption that the quantitative flying qualities requirements of MIL-F-8785C, when not given explicitly as a function of turbulence, are implicitly based on a moderate turbulence environment.

Thus, to meet the requirements here of 3.1.11.2.2, the probability calculations of 3.1.6.1 are performed as described with one specific

injunction. The RSS requirements for a specific Flying Qualities Level should be those for the design turbulence environment, as defined by Table 2 (3.1.11.2.2) or, lacking that or other definition, as defined for moderate turbulence. Then the degradation of flying qualities Level with turbulence for RSS Failure States may be estimated using the criteria and supporting data from the RSS requirements, though in general, pilot ratings from simulation in various turbulence intensities will be required to define the degradation of flying qualities due to turbulence for the various Failure States. These results are then used to calculate the probabilities for comparison with the requirements of Table 2 (3.1.11.2.2).

The generic failure analysis of 3.1.6.2, given as an alternative approach, makes little sense in the context of the relaxed static stability (RSS) where the degree of RSS is significant and an essential FCS augmentation function is required for flight safety. If one assumes, as prescribed in 3.1.6.2, that the essential FCS has failed, then the only logical consequence is to presume loss of control and loss of the airplane, otherwise why the essential FCS (a dead end). Alternatively, failure of the essential FCS can be declared a Special Failure State, in which case its failure need not be considered. But, once the airplane is built and flying, what is to prevent the essential FCS from failing with consequent loss of control and loss of the airplane (another dead end). The only solution is to design the essential FCS to have high reliability, using analysis based first on empirical reliability data and experience, then analysis based on laboratory component tests as the design proceeds, and lastly based on whole system reliability tests. Finally it is hoped that the airplane, as it goes through flight test and operational use, demonstrates reliability that validates or improves on the reliability predictions and that the aircraft loss rate is acceptable or better (a desirable end). And we have just described the probability analysis approach of 3.1.6.1. Granted, there are various degrees between the two example extremes of the generic approach. However, they will all lead to the same conclusion. Without a probabilistic approach, employing careful reliability analyses supported by extensive testing, the use of RSS must be relegated to rather trivial cases and its potential benefits foregone.

G. DEMONSTRATION OF COMPLIANCE

Procedures are the same as those outlined in 3.1.6.1 and as amplified under 3.1.10 of Reference 2. The primary method for validating the effects of failures material to relaxed static stability augmentation must be piloted simulation because of flight safety considerations with respect to flight test. Emphasis must be placed on extreme conditions, e.g., extremes in maneuvers, angle of attack, turbulence, and the effect of failure occurrence during these. Also, emphasis must be placed on piloted simulation tests with respect to turbulence effects because of the impracticality of flight testing at prescribed turbulence intensities. However, simulation test results should be validated by flight test results as they are obtained from the encounters with real atmospheric disturbances that will occur during the normal flight test program.

3.2.1.3 RSS Pitch Attitude Response to Pitch Controller

A. REASON FOR THE REQUIREMENT

Relaxed static stability primarily affects the response of pitch attitude, and most of the requirements can be expressed in terms of the response of pitch attitude to pitch control input. The use of relaxed static stability implies the use of stability augmentation to achieve satisfactory flying qualities. The first purpose of this paragraph is to explicitly state that the Normal State requirements, with augmentation, are not relaxed nor modified. The second purpose is to ensure with sufficient probability that, after a pitch augmentation failure or with nonessential augmentation OFF, the pitch attitude response will have characteristics that enable the airplane to safely reach a terminal destination (original, alternate, or home base) and land.

B. RELATED MIL-F-8785C REQUIREMENTS

3.2.1.1, 3.2.1.2, 3.2.2.1, 3.2.2.2, 3.2.2.3

C. STATEMENT OF THE REQUIREMENT

3.2.1.3 RSS pitch attitude response to pitch controller. Aircraft having relaxed static stability, as identified in 3.1.11 and defined in 3.1.11 of the Handbook, are required to meet 3.2.1.1 and 3.2.1.2 and also 3.2.2 and 3.2.3 for the flight control system in Normal State with pitch augmentation ON, and unfailed. For Failure States of the flight control system (pitch augmentation OFF or failed), the Level 2 and 3 requirements for pitch attitude response to pitch control input (3.2.1.1 and 3.2.1.2) and for PIO's (3.2.2) and residual oscillations (3.2.3) are modified to the following: ______________.

D. RECOMMENDATIONS

Approach and Landing (PA, L)

Two forms of criteria are specified as requirements for the pitch attitude response to pitch control input, a parametric criterion applicable to a limited range of aircraft characteristics and a more general frequency response criterion. It is recommended that, where applicable, the requirements of both criteria be met.

Parametric Criteria for Approach and Landing

The aircraft transfer function for pitch attitude to pitch control input is placed in the following form (or equivalent form). A lower-order equivalent system, as defined in 3.2.1.1 of the Handbook, may be used, but the actual system must be matched in three degrees of freedom (θ, n_z, V) for $0.1 < \omega < 10$ rad/sec.

$$\frac{\theta}{F_S} = Y(s)_{cs} \quad \frac{A_\theta(s - Z_{\theta_1})(s - Z_{\theta_2})}{(s - \lambda_{sp_1})(s - \lambda_{sp_2})(s^2 + \zeta_p \omega_{n_p} s + \omega_{n_p}^{\ 2})}$$

where

$Y(s)_{cs}$ higher order dynamics of feel system, actuators, filters, etc., with no zeroes or roots <10 rad/sec nor phase lag $>5.73\,\omega$ degrees (ω in rad/sec). For equivalent form, $Y(s)_{cs} = e^{-\tau_e s}$ with $\tau_e \leq 0.1$ sec (applies to all levels).

Z_{θ_2} large zero of θ/F_S, $-1/T_{\theta_2}$; $.2 < -Z_{\theta_2} < 2$ rad/ sec

Z_{θ_1} small zero of θ/F_S, $-1/T_{\theta_1}$; $0 < -Z_{\theta_1} < .3$ rad/sec

ω_{n_p} phugoid frequency (rad/sec), $\omega_{n_p}{}^2 < .09$

ζ_p phugoid damping, $\zeta_p > 0$

λ_{sp_1} most positive real root, short period

λ_{sp_2} most negative real root, short period

The real short-period roots (λ_{sp_1} and λ_{sp_2}) must then lie within the boundaries shown on Figure 1 for Levels 2 and 3 for the appropriate intensity of turbulence and Z_{θ_2} and $M_{\delta_{ES}}$ within the prescribed limits.

If Z_{θ_2} is outside the prescribed limits for Figure 1, or $M_{\delta_{ES}}$ is less than the prescribed range, then the following method for determining the Level applies using pilot ratings (PR).

PR = PR (Fig 1) + Δ PR (Fig 2) + Δ PR (Fig 3)

Level 2	PR $\leq$ 6.5
Level 3	6.5 < PR $\leq$ 8.5
Level >3	PR > 8.5

In Figure 1, PR is constant with λ_{sp_2} above the line labeled "critical"; below this line PR is interpolated with λ_{sp_2} using the labeled values on the critical line and the 6.5 and 8.5 boundaries. PR is constant with λ_{sp_1} to the left of $\lambda_{sp_1} = .115$.

The correction for Z_{θ_2} from line (b) of Figure 2, for which λ_{sp_2} is below the critical line on Figure 1, is limited so that PR (Fig 1) + PR(Fig 2) is not less (better) than PR on the critical line for the given value of λ_{sp_1}.

No correction is available for high sensitivity, and if $M_{\delta_{ES}} > .55$ rad/sec^2/in, it must be demonstrated that such values do not cause PIO's, particularly in flare and touchdown.

$-.5 > Z_{\theta_2} \approx -1/T_{\theta_2} > -.7$

$.25 \leq M_{\delta_{ES}} \leq .55$ rad/sec²/in

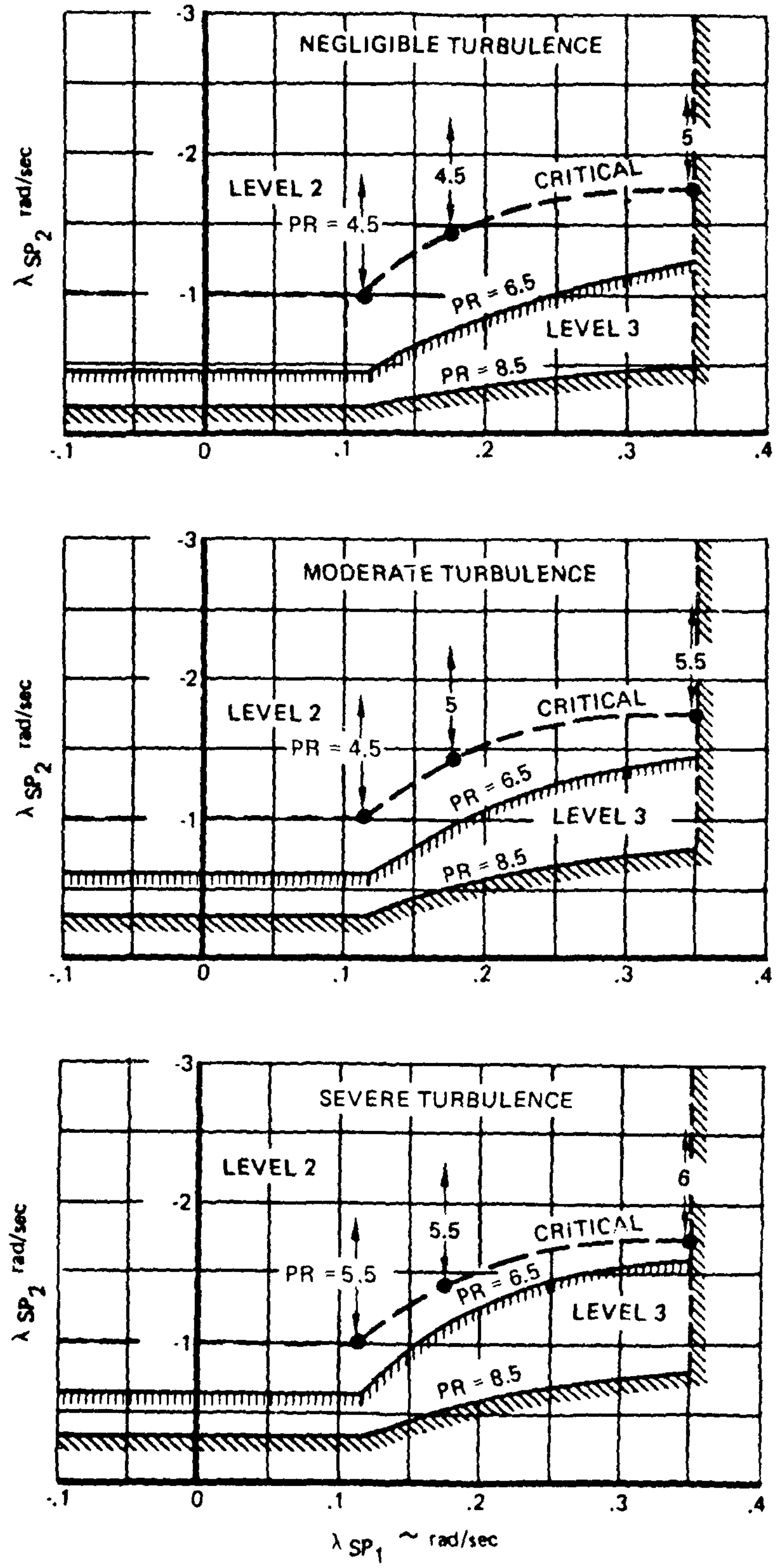


Figure 1 (3.2.1.3). RSS Criteria for Short-Period Roots (λ_{SP_1}, λ_{SP_2}) in Approach and Landing

$.25 \leq M_{\delta_{ES}} \leq .55$ rad/sec²/in

PR = PR (Figure 1) + ΔPR ; but PR limited to no better (less) than PR_{CRIT} at λ_{SP_1}

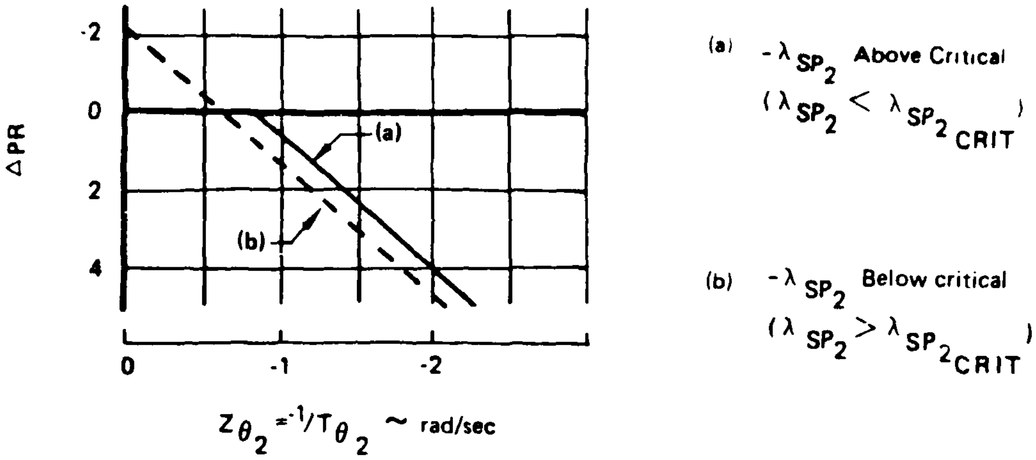
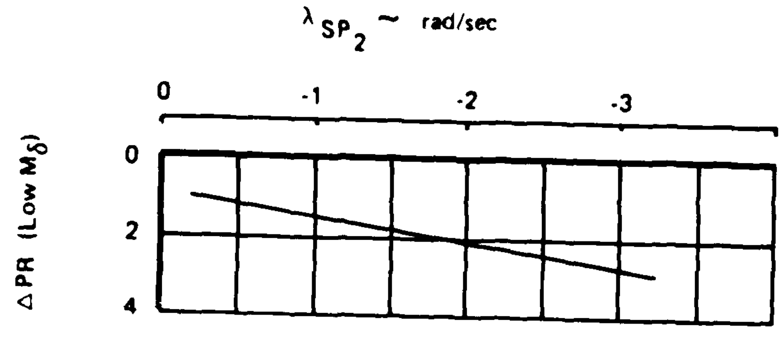


Figure 2 (3.2.1.3). Correction for Z_{θ_2} to RSS Criteria for Approach and Landing

Apply correction for $.08 \leq M_{\delta_{ES}} < .25$ rad/sec²/in

Average ΔPR for all turbulence levels

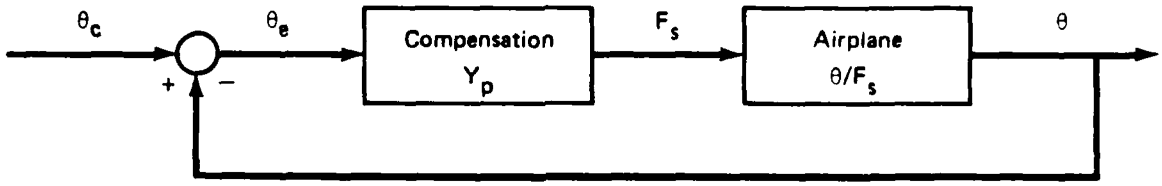


PR = PR (Figure 1 & 2) + ΔPR (Low M_δ)

Figure 3 (3.2.1.3). Correction for Low Control Sensitivity to RSS Criteria for Approach and Landing

Frequency Response Criteria for Approach and Landing

The criterion is applied by enclosing the pitch attitude to pitch control transfer function (or its equivalent) together with forward loop compensation (Y_p) in an attitude command loop.



$\frac{\theta}{F_s}$ Transfer function or describing function of pitch attitude response to stick force input for airplane and flight control system.

$$Y_p = K_p e^{-0.3s} \frac{(\tau_{p_1} s + 1)}{(\tau_{p_2} s + 1)} (\tau_{p_3} s + 1)$$ Permitted form of compensation

The closed-loop resonant amplitude (RA) and compensation lead (ϕ_{PL}) shall lie within the boundaries shown on Figure 4 for bandwidths (BW) of both 1 and 3 rad/sec for Levels 2 and 3. The attitude-command loop closure shall be performed in the following manner.

Definitions:

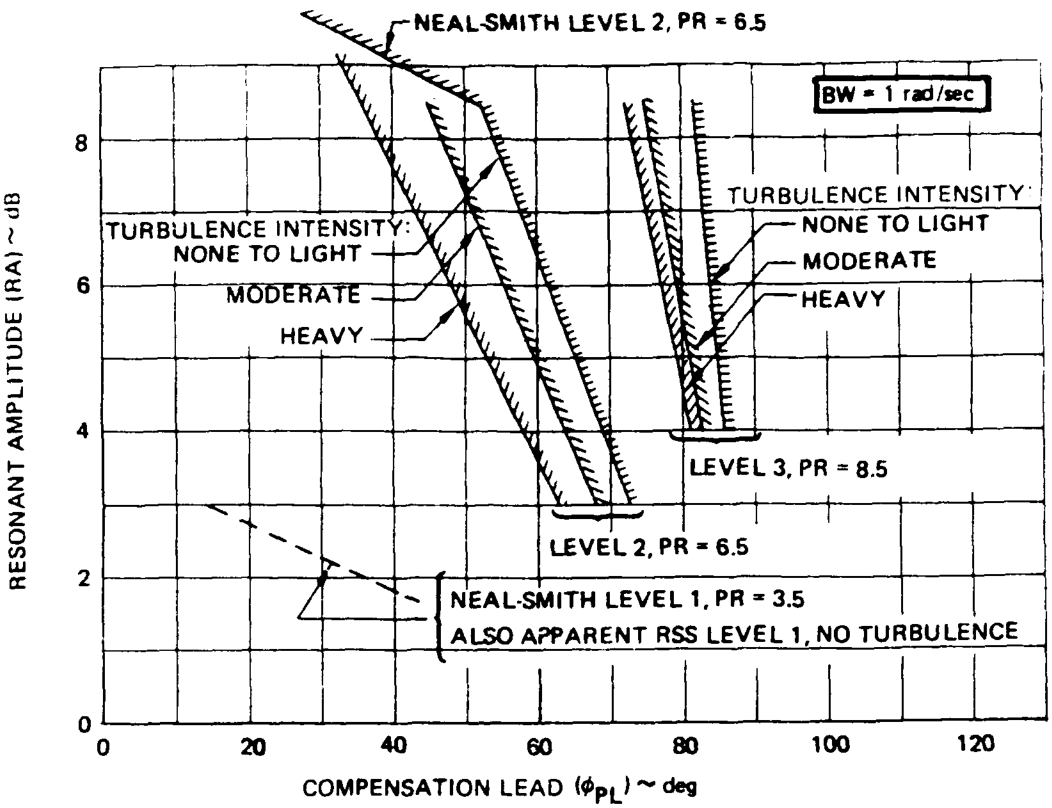
RA Resonant amplitude: $\left|\frac{\theta}{\theta_c}\right|_{max}$ for $0.1 < \omega < 10$ rad/sec

ϕPL Compensation lead: phase lead of Y_p at BW, not including time delay ($e^{-0.3s}$),

BW Bandwidth: ω for $\measuredangle \left|\frac{\theta}{\theta_c}\right| = -90^\circ$

Droop $\left|\frac{\theta}{\theta_c}\right|_{min}$ for $\omega \leq$ BW

CRITERIA ASSUME A SATISFACTORY LEVEL OF CONTROL SENSITIVITY.



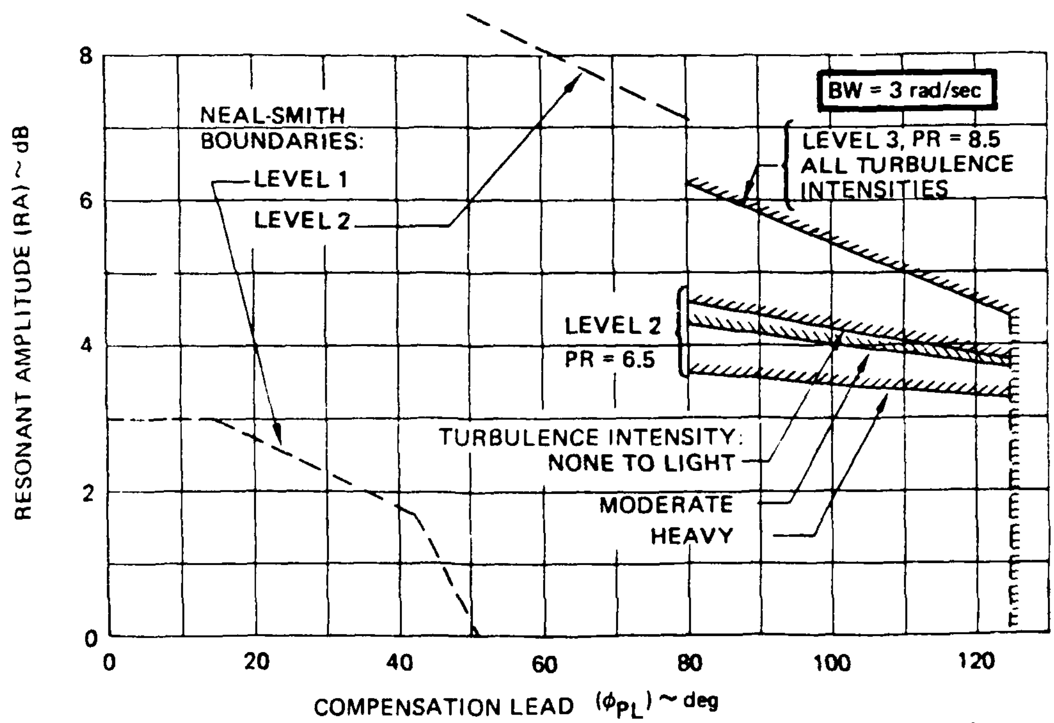


Figure 4 (3.1.2.3). Frequency Response Criteria for Pitch Attitude Dynamics of RSS Airplanes in Approach and Landing

Loop Closure Procedure:

For separate closures at BW = 1 and 3 rad/sec, the gain (K_p) and compensation (τ_{p_1} and τ_{p_2}) shall be adjusted to yield minimum compensation lead (ϕ_{PL}) or lag ($-\phi_{PL}$) while maintaining the following closed loop characteristics:

Droop = -3 db for $0.1 < \omega <$ BW rad/sec

Droop = 0 db for $0.1BW < \omega <$ BW

(i.e., minimum value of $|\theta/\theta_c|$ must lie between 0 and -3db, with due regard for applicable ω bands)

There are no constraints on K_p, τ_{p_1} or τ_{p_2}, but τ_{p_3} must be set so that

$$1/\tau_{p_3} = BW$$

Correction for Control Sensitivity:

When control sensitivity falls outside the acceptable range ($.25 \leq M_{\delta_{ES}} \leq .55$ rad/sec^2/in), then the method for correcting it shall be as in the parametric criteria using data in Figures 3, 16 and 18.

Category A and Some Category C Flight Phases

For all Category A flight phases and those Category C flight phases requiring precise attitude control, the parametric criteria of Figures 1, 2, and 3 should be applied where the parameters fall within the ranges of the criteria. The frequency response criteria of Figure 4 should, however, be met for all these flight phases including those where the parametric criteria apply.

Category B and Some Category C Flight Phases

For all Category B flight phases and those Category C flight phases not requiring precise attitude control (e.g., TO, CT, WO), the frequency response criteria of Figure 4 should be met for BW = 1 rad/sec.

For all Category B flight phases that are maintained for extended periods of time, in excess of 10 minutes, the Level 2 and Level 3 requirements shall be the same and equal to the Level 2 requirements of

Figure 4 for BW = 1 rad/sec. This more severe requirement for extended flight time with relaxed static stability can be met by changing to an alternate flight condition or configuraton where the relaxed stability is less severe (e.g., higher or lower airspeed or altitude, fuel transfer forward, wing sweep change, partial flap extension).

The parametric requirements of Figures 1, 2, and 3 may be used as design guides for these Category B and C flight phases, but they are overstringent for short periods of flight, and insufficient for long periods of flight depending on the additional duties required of the pilot and the availabiity of more than one pilot to fly the aircraft.

All Flight Phases

It shall be the responsibility of the contractor to show that Level 2 or Level 3 flying qualities are maintained while the pilot is performing all duties and responsibilities required of him, over and above those of the primary control task, in all flight phases where relaxed static stability effects are present. This requirement should be met using simulation, verified where safe by flight test. Where extended flight times, use of more than one pilot, or interfaces with other crew members are involved, these should be included in the simulation.

Long Period Oscillation

The requirements of 3.2.1.1 for the phugoid or long period oscillation do not apply and need to be modified for statically unstable aircraft. The suggested measurement technique cannot be used as the response to a pulse input will generally be divergent, stick fixed or stick free. Normally if the frequency response requirements are met, this will ensure adequate phugoid characteristics. However, where the effects of relaxed static stability are present, it is desired that the phugoid roots be stable, $\zeta_p > 0$, and of low frequency, $\omega_{n_p} < .3$ rad/sec, or if real, λ_{p_1} and $\lambda_{p_2} < .3$ rad/sec. Demonstration shall be analytical, supported by flight test results. The above conditions shall be met for Level 2 and Level 3, or the contractor shall demonstrate that Level 2 or Level 3 flying qualities are not degraded otherwise, by simulation, and subsequently flight test.

Pilot Induced Oscillations

For aircraft with relaxed static stability, especially for the more unstable aircraft, there will be a tendency for sustained low-frequency small-amplitude oscillations, that is, limit cycles. They are pilot induced oscillations (PIO) in that they are a product of the closed-loop pilot-airplane combination. Thus the requirements of 3.2.2 cannot be met for RSSAS failures (pitch augmentation OFF or failed), and the following apply instead. For Level 2, the PIO amplitude should not be objectionable to the pilot, and should be characterized at worst as a mild PIO tendency. For Level 3, the PIO amplitude should not interfere with the pilot's ability to control the airplane safely, and should be characterized at worst as an objecionable but clearly controllable PIO tendency. The limit cycle or PIO frequency should in no case exceed 3 rad/sec. [See RATIONALE for basis.]

Residual Oscillation

The requirements of 3.2.3 do not apply to the above pilot induced oscillations. For statically stable airplanes, by virtue of partial or back-up augmentation or inherent natural but relaxed stability, the Level 2 requirements do apply for residual oscillations with frequency less than 3 rad/sec. For frequencies above 3 rad/sec, the Level 2 requirements of 3.2.3 apply for all failure states with relaxed static stability. For Level 3, any residual oscillation with frequency equal to or above 3 rad/sec shall not interfere with the pilot's ability to safely control the airplane. [See RATIONALE for basis.]

Flight Path Stability

Flight path stability, defined as in 3.2.1.2 of MIL-F-8785C, shall be such that

$$\left|\frac{d\gamma}{dV}\right|_{\substack{\text{constant}\\ \text{throttle}}} \leq 0.06 \text{ deg/knot}$$

This requirement applies to the landing approach flight phase (PA) for all levels. In the event it is not met, then it shall be the responsibility of the contractor to show that Level 2 or 3 flying qualities are not degraded by more positive values of $d\gamma/dV$. Demonstration shall be by simulation, supported by flight test. [See RATIONALE for basis.]

C. RATIONALE BEHIND THE REQUIREMENT

The major effects of relaxed static longitudinal stability, control power requirement excepted, are dealt with in this requirement. The requirement for relaxed static stability in 3.2.1.1 of MIL-F-8785C is a time to double amplitude (T_2) of 6 seconds or more for Level 3. This T_2 = 6 sec requirement has generally been considered the maximum safe divergence rate. However, this value has been controversial, since simulator and flight test data have shown it to be at times too stringent and conservative, at other times too lax and insufficient. The results in Appendix B of this report show that T_2, by itself, is not a valid criterion for flying qualities, and other parameters in the θ/F_S transfer function have a vital influence. For example, with a T_2 = 6 seconds, flying qualities ranged anywhere from a pilot rating of 3 (Level 1) to 10 (worse than Level 3) depending on the value of the other parameters. Clearly new criteria are needed for relaxed static longitudinal stability.

The criteria for relaxed static stability, as stated here, are based primarily on the simulation results in Appendix B of this report. The simulation was for the terminal area and included instrument flight while acquiring and maintaining ILS glide path, and visual flight during short final, flare, and touchdown. The results are, however, supported by the flight test data of Reference 8. Though the criteria were developed for the approach and landing task, because it appeared to be the most critical, there is every reason to believe the criteria can be extended to other flight phases and conditions with judicious modification. Clearly, additional verification is needed. In applying the requirements the contractor should make early use of simulation, to verify the

requirements for his airplane, and to cover extrapolation and open areas. Though the stated requirements have less than the desired amount of supporting data, still they are far more likely to provide valid criteria than the current MIL-F-8785C criterion with its demonstrated lack of validity.

Relaxed static stability of significant degree changes the arrangement of airplane roots in the linearized or transfer function representation of the airplane. The separation of high-frequency short period and low-frequency phugoid no longer holds, though a constant speed approximation can still be made. From pilot comments taken during various flight test and simulation programs, it is clear that airplane pitch attitude (θ) is the response variable primarily affected by relaxed static stability, and therefore θ/F_S should be primary in any adequate RSS criteria. The fixed-base ground simulator investigation (App. B) examined parametrically the effects of the various quantities in the θ/F_S transfer function (as given previously) and found that λ_{sp_1}, λ_{sp_2} and Z_{θ_2} are dominant on the short-term time response, the frequency response in the range $.3 < \omega < 3$ rad/sec, and pilot rating for low-speed flight in approach and landing. Furthermore, the most positive real root (λ_{sp_1}), the most negative real root (λ_{sp_2}), and the large zero (Z_{θ_2}) can be labeled short period, as they define the short term response and are closely related to the constant speed roots; while the remaining roots (λ_{p_1} and λ_{p_2}, defined by ζ_p and ω_{n_p}) and the small zero (Z_{θ_1}) can be labeled phugoid, as they are directly related to speed change and disappear under the constant speed assumption in level flight. If λ_{sp_1} is small, negative or positive ($T_{1/2} \simeq 6$ sec to $T_2 \simeq 6$ sec), the airplane can be considered neutrally stable and pilot rating varies little in this range. The small short-period root (λ_{sp_1}) and the phugoid roots tend to coalesce (form three real roots) for some c.g. values and become indistinguishable. Fortunately this whole area appears to be unimportant since the c.g. variation to cover it is < 1% m.a.c., and flying qualities don't change over it. So, it can be conveniently lumped into the single category of neutral stability.

Parametric Criterion

The parametric criterion is in the following functional form,

$$PR\,(\lambda_{sp_1}, \lambda_{sp_2}, Z_{\theta_2}, M_{\delta_{ES}}) = PR_0(\lambda_{sp_1}, \lambda_{sp_2}) + \Delta_1 PR(Z_{\theta_2}) + \Delta_2 PR(M_{\delta_{ES}})$$

where PR is the pilot rating and is converted to Level as specified. The simulator data (App. B) appear to fit this form and are the only known data with independent variations of λ_{sp_1}, λ_{sp_2}, and Z_{θ_2}. Though it has shortcomings, this form of criterion is included as a primary criterion for relaxed static stability because it is simple in structure, relates familiar parameters to Levels and pilot ratings, and requires no special computer program or complex analytical process to go from airplane characteristics to flying qualities Level, or the reverse.

The criterion is specifically designated as an approach and landing criterion because the data it is based on, ground simulation and some flight test, were for that task (with some low-speed airwork inbound prior to ILS acquisition). Turbulence is included as a parameter in the basic variation of $PR(\lambda_{sp_1},\lambda_{sp_2})$ in Figure 1 because it has such a strong influence; e.g., at a given value of λ_{sp_1}, the value of λ_{sp_2} for Level 3 is 50% higher for severe turbulence than smooth air. The Level boundaries in Fig. 1 between λ_{sp_1} = .1 and .35 ($T_2 \simeq$ 6 sec to 2 sec) are reasonably well supported by the data. The vertical boundary along λ_{sp_1}=.35 is an arbitrary cut-off, made there because there is no data for $\lambda_{sp_1} > .35$ ($T_2 < 2$ sec), even though the data showed no evidence of degrading flying qualities with increasing λ_{sp_1}. However, the data for low M_δ (Fig. 9 (3.2.1.3), $M_{\delta_{ES}}$= .085 rad/sec^2/in) indicate that a sharp turn-up of iso-rating lines may occur, and motivates the cut-off at λ_{sp_1} = .35 for both Level 2 and 3. The portion of the boundaries for $\lambda_{sp_1} < .1$ are extrapolations, also based on the same low M_δ data, but are believed to be reasonably correct. The critical line separates the λ_{sp_1}, λ_{sp_2} plane into two regions. Above the critical line, pilot rating does not vary with λ_{sp_2}. Below it, pilot rating degrades rapidly as λ_{sp_2} becomes less negative. The constancy of PR with λ_{sp_2} above the critical line may be misleading, since the data on which Figure 3 is based indicates that the optimum value of M_δ increases as λ_{sp_2} gets larger negatively

(i.e., more stability requires more sensitivity). So the constant PR may result from two trends, improved PR with more negative λ_{sp_2} balanced by degraded PR due to increasingly insufficient M_δ. The criteria in Figure 1, and the data on which they are based, are for a specific value of Z_{θ_2} ($\simeq$ -.6) and a narrow range of M_δ. In fact, specific values of $M_{\delta_{ES}}$ in the data were .34 rad/sec²/in for the simulation (App. B) and a nominal .43 rad/sec²/in for the in-flight simulation (Ref. 7). The indicated range (Fig. 1) is 25% above and below these two values. This 25% allowed variation is based on undocumented variations performed in the simulation during prelimnary evaluations, and the variations found in the flight test results. Format and range of parameters for the criteria of Figure 1 were selected to cover the available data, including the low M_δ data which were used to extrapolate in the $-0.1 < \lambda_{sp_1} < 0.1$ range.

The use of pilot rating in the criteria is to enable a correction to be made for Z_{θ_2} and $M_{\delta_{ES}}$ different from those specified in Figure 1. The equivalence for Level and pilot rating is the one commonly used except for the Level 3 minimum. Normally, this minimum is set at PR = 9.5 rather than 8.5. However, the definition of Level 3 says, "Category A - terminated safely, Category B and C - can be completed," so clearly the airplane must be safe to land. A PR = 9 has "intense (maximum) pilot compensation required to retain control" while for PR=10 "control will be lost." A boundary between a rating which requires maximum effort to retain control and a rating where control will be lost despite maximum effort would hardly seem safe.

To meaningfully establish an equivalence between pilot rating and the Level 3 boundary, it is important to understand what it means to retain control in the landing task. First, it means that while the pilot may be readily able to execute a wave-off, a necessary ability, this is not evidence of controllability in landing. The pilot must be able to retain control in the landing itself. Secondly, controllability in the landing means the airplane can be landed safely, without injury or damage. So the pilot must have enough control to land on the runway, and early enough so the airplane doesn't go off the end. These definitions

were applied and are quantified in Appendix B for the specific landing task used in the simulator investigation. There, wave-offs (at least one) were allowed in the process of completing a safe (controllable) landing.

For a PR = 9 there is no margin for error in the landing as the pilot is working at maximum to retain control. Loss of control means an unsafe landing (off the runway, crash, etc.) or a go-around. But if a go-around is safely negotiated, the pilot is still faced with another landing. On the other hand, PR = 8 has "considerable pilot compensation required for control," so a boundary at PR = 8.5 allows some margin and seems far more consistent with the definition of Level 3 as safe to land.

It should be noted that, though PR = 8.5 is appropriate for the Level 3 boundary for landing, the appropriate Level 3 boundary for most tasks would be PR = 9.5 since most tasks can be aborted and safe recovery made to a less demanding task. The landing is unique. Though a landing may be aborted and a go-around safely executed -- there is no escape -- the airplane must be landed.

The correction for Z_{θ_2} shown in Figure 2 is based on independent variations in this parameter from two baseline configurations of the data base for Figure 1. The increment in pilot rating was not significantly affected by turbulence. But the data, though sparse, did seem to be affected by whether the λ_{sp_1}, λ_{sp_2} combination was above or below the critical line in Figure 1. Accordingly two correction curves, line (a) and line (b), are given in Figure 2 which differ in intercepts but not in slope. Another observation was that for λ_{sp_2} on the critical line, the pilot rating appeared to be the best rating obtainable with varying Z_{θ_2}. The observation is reflected in correction curve (a) on Figure 2 being cut-off at PR = 0, and the note on Figure 2 indicating that PR should be cut off at the appropriate level (affects only curve (b)).

The correction for a too low control sensitivity, Figure 3, is based on an inadequate amount of data - a data set with just one value of $M_{\delta_{ES}}$ (.08 rad/sec^2/in) different from the baseline of Figures 1 and 2. However, the basic trend shown in Figure 3 is correct: a degradation in pilot rating, proportional to $-\lambda_{sp_2}$, with $M_{\delta_{ES}}$ at less than a satisfactory sensitivity. The increment shown in Figure 3 is that

associated with the low M_δ data set. Application of the discrete increment of Figure 3 for the indicated M_δ range is conservative. Interpolation between the two M_δ data sets would be reasonable; extrapolation to lower values would be risky. Including this correction considerably broadens the applicable scope of the criteria and provides an appropriate penalty for inadequate control sensitivity.

A last note on the basis for the criteria relates to control force gradient. All the data, both simulation and flight test, upon which the criteria are based had about a 7 lb/in stick force gradient. So, the specification of control sensitivity could have been in terms of stick force sensitivity ($M_{F_S} = M_{\delta_{ES}} \frac{\delta_{ES}}{F_S}$) instead.

It is important to understand that the control technique required to fly a statically unstable airplane is distinctly different from that used with stable airplanes. The pilot controls with a lot of lead, uses pulse inputs, or as one pilot put it, "spikes." Conventional force gradients with motion variables, such as stick force per g, are relatively meaningless. The pilot must be able to pulse the controls and put in large inputs easily, and there must be adequate response in angular acceleration. So control forces must be light and control motions not too large. Apparently pilots readily adapt to the different technique. No real problem is encountered going from a stable to an unstable airplane as the result of a failure. The change in control technique occurs almost automatically, and for better unstable configurations (Level 2) the pilot may not even realize for awhile that the airplane is unstable (see Appendices B and G, also Ref. 8 and 22).

Frequency Response Criteria

The parametric criteria, though appealingly simple, have shortcomings. The criteria can take into account only those parameters which have been systematically varied in experiments, and only for the range of values of the parameter investigated, and only for the baseline conditions for other characteristics and parameters. For example, there

is nothing in the parametric criteria that accounts for changes in feel system dynamics, control system dynamics, or phugoid characteristics. Furthermore, parametric criteria cannot treat a number of characteristics simultaneously, and the criteria must involve parameters independently, two at a time at most. The frequency response criteria given here and developed in Appendix B of this report have the desired generality and meet the shortcomings of the parametric criteria.

The fundamental assumptions are that the pilot closes an attitude loop around the airplane, adjusting his compensation to achieve desired closed-loop performance, and that flying qualities depend on the performance achieved and the compensation required. Furthermore, it is assumed that if an attitude loop is closed around the θ/F_S transfer function with forward-loop compensation of the appropriate form, then flying qualities or pilot rating can be correlated and predicted as a function of closed-loop performance and compensation parameters. Though not necessary, it is intuitively gratifying and lends credibility if the compensation has the form of recognized analytical models for the pilot, and the closed-loop response characteristics have their counterparts identifiable in simulator and flight test time histories.

Rationale for the frequency response criteria for relaxed static stability starts with the Neal-Smith criterion (Ref. 7). Relaxed static stability requires substantial lead compensation for the attitude loop, more than for stable aircraft, and generally above 90° for the higher bandwidths. A second lead term $(\tau_{p_3}s+1)$ has been added to the compensation or pilot model used by the Neal-Smith criterion, as indicated by the diagram and equation for Y_p given with the criterion earlier. The selection of $1/\tau_{p_3}$ = BW allows 45° more lead at the bandwidth frequency than the Neal-Smith compensation, and a usable lead up to about 125° (distortion occurs if the last 10° of possible lead is used). The justification for using this much lead comes first from the facts that pilots do fly unstable configurations quite successfully, that based on pilot comments they use an attitude loop in the process, and that to do so with an attitude loop must mean that they provide

lead > 90^0. Secondly, the characteristics of pilots extracted by Sudderth, et al. (Ref. 22) show pilot lead well in excess of 90^0, to 180^0 in some cases. What this means is that the pilot not only senses attitude angle, but also pitch rate and angular acceleration, and processes this information and inserts it as an input to the stick. Viewed in this sense, lead in excess of 90^0 seems readily understandable. The selection of $1/\tau_{p_3}$ = BW was arrived at, as described in Appendix B, based on examining the effect of a wide range of values of τ_{p_3}. This selection was the most satisfactory one, and provided enough lead to handle all cases of relaxed static stability studied (to $\lambda_{sp_1} = .35$ or $T_2 = 2$ seconds). As also shown in Appendix B, for most cases of relaxed static stability, the value selected for τ_{p_3} has no effect on the compensation or pilot lead at a given value of bandwidth, because of the shape of the frequency response near the bandwidth (large positive $dA/d\phi$), and because of the form of the criterion (it usually forces a specific value of lead at bandwidth regardless of pilot model form).

The performance standards and the method of closing the attitude loop are distinctly different from the procedures of Neal and Smith (Ref. 7). The procedures developed in this report (App. B), specifically for relaxed static stability, are based on examining a number of possible procedures, attempting correlation of the results with the pilot rating data, and comparing the results with simulator and flight test time-history data and pilot comment data. Rationale for the separate aspects of the procedure follow.

The frequencies found in the experimental time histories and the pilot comments show very clearly that the pilot does not close the loop with a constant gain to achieve a fixed bandwidth. Rather, the pilot varies gain and bandwidth as he flies, in response to the demands of the immediate situation or task. Thus it appears that the concept of fixed gain and bandwidth, as used by Neal and Smith and others since, is an oversimplification of the situation, and a frequency response criterion must take into account a range of bandwidths. For the attitude loop closure, this range of bandwidths appears to be from 1 rad/sec or less to

3.5 rad/sec. Two criterion frequencies, BW = 1 rad/sec and BW = 3 rad/sec, are selected as representative of the bandwidth range used by the pilot, and criteria are applied to the results of attitude loop closures at each of these frequencies separately. The BW =1 rad/sec loop closure is the primary one for relaxed static stability effects, as these effects center about a frequency of 1 rad/sec. Above about 4 rad/sec, the effects of relaxed static stability are negligible. Much below 0.3 rad/sec the effects of relaxed static stability may be large (phase shift of -180^0 from stable to unstable) but they are not germane to the attitude loop closure with pitch control. The BW = 3 rad/sec loop closure is primarily related to control system and higher order dynamics, and concerned with higher frequency PIO's, much as the standard Neal-Smith criterion. Flying qualities criteria must be met for both bandwidths.

The loop closure procedure specifies that compensation parameters shall be adjusted to yield minimum lead subject to the amplitude or droop constraints. This minimization is at distinct variance with the original Neal-Smith requirement for minimum resonant amplitude, which usually requires more pilot lead, forcing a -3 db droop. The difference in approach is due to the difference in airplane characteristics. The Neal-Smith criterion deals with the PIO problem caused by higher order dynamics which can cause large resonances at high frequencies, above the bandwidth (3.5 rad/sec in Ref. 7). The RSS criterion deals with low frequency oscillations (PIO's), limit cycles, and divergences caused by low frequency airplane lag and the need for excessive pilot lead. In the RSS case, compensation or pilot lead is the primary problem reflecting the workload. Closed-loop resonant amplitude, at least in the analytical representation, is of secondary importance.

The droop constraints (Droop $\equiv$ min $|\theta/\theta_c|$ for ω < BW) for the relaxed static stability criteria are also modified from the Neal-Smith constraints. While Neal-Smith simply requires Droop $\geqslant$-3 db, the RSS criterion constrains Droop $\leqslant$ 0 db for frequencies from 0.1BW to BW, and Droop $\geqslant$-3 db for frequencies from 0.1 rad/sec to BW. Thus the RSS criterion constrains droop to an amplitude band of 0 to -3 db. The primary constraint is the 0 db limit, as this is the one that defines the

minimum compensation or pilot lead. Usually for minimum pilot lead with RSS, the droop condition will be met at bandwidth frequency and closed-loop phase of -90^{o}. (Full development given in B.6.1, Appendix B.)

The rationale for the loop closure procedure, different from the Neal-Smith one, is again based on the findings reported in Appendix B of this report. Attempted correlation of pilot rating with compensation (pilot) lead, closed-loop resonant amplitude, and other parameters for BW = 1 rad/sec clearly showed that pilot lead was the dominant factor. Furthermore, simulator time histories exhibited low frequency oscillations (PIO tendency) which for the worse RSS configurations were somewhat correlated in frequency with the peaks in the calculated closed-loop response, but the large resonant amplitudes indicative of a sustained PIO simply were not present in the calculated closed-loop response. Since pilot lead is clearly a measure of pilot work load, and analytical closed-loop resonance is modest, the logic of using minimum compensation lead (instead of minimum resonant amplitude) in the relaxed static stability criterion seems inescapable.

Rationale for the specific form of the droop constraint comes from Appendix B of this report, Section B.6.1.3. As can be readily seen from a Nichols chart (e.g., Fig. 5), pilot lead decreases with droop (as min $|\theta/\theta_c|$ becomes more positive). However, as droop becomes positive (droop > 0 db), the closed-loop response at low frequencies is forced to large amplitudes, within the closed contours about the open loop -1 point in the Nichols chart. Thus the upper limit for droop is established as 0 db, and becomes normally the condition for minimum pilot lead. Phugoid characteristics can produce a low amplitude and minimum open-loop phase condition at frequencies below the phugoid natural frequency, $(\omega \to 0)$, especially for $1/T_{\theta_1}$ much less than phugoid natural frequency. This low amplitude condition will result in low frequency closed-loop droop. On a Nichols chart, the frequency response loops around clockwise and can easily have a lower closed-loop droop than 0 db $(\omega \ll BW)$ when the curve at or near bandwidth $(\omega < BW)$ has a minimum of 0 db (e.g., Figure B-36(a) and (b) of this report). Since the object of the 0 db upper limit for droop is to provide a bound for minimizing compensation (pilot) lead (defined at bandwidth), and since

the effect of the phugoid or speed change at frequencies well below the bandwidth is irrelevant to the pilot's closure on attitude, the upper bound for droop (0 db) is limited to $\omega > 0.1BW$. In fact, under most circumstances, this limit could be raised to $\omega > 0.3BW$. However, the lower bound on droop (-3 db) is extended all the way down to 0.1 rad/sec, well below the minimum frequency of 0.5 rad/sec considered pertinent by Neal and Smith (Ref. 7), to ensure there will be no objectionable low frequency droop in the closed-loop attitude response.

The criterion for pitch attitude dynamics for relaxed static stability as a function of closed-loop resonant amplitude (RA) and compensation lead (ϕ_{PL}), including Level 2 and 3 requirements, comes directly from Appendix B of this report, Figure B-52. The criterion is based on correlations of pilot rating data from ground simulation, supported by validation of the simulation results with LAHOS flight test data from Smith (Ref. 8).

<u>BW = 1 rad/sec</u>. The correlation of pilot rating with RA and ϕ_{PL}, leading to the Level 2 and 3 boundaries in Figure 4, was very good with few anomalous points. The criterion takes into account variations of the short period roots (λ_{sp_1},λ_{sp_2}) and the large θ/F_S zero (Z_{θ_2}). It should be able to take into account phugoid dynamics and the effects of lower frequency higher-order system characteristics (filters, washouts, feedback loops). Additional verification would be desirable, particularly for the latter effects, with a wider range of conditions and parameters than was used in the simulator investigation (App. B). The criteria at BW = 1 rad/sec are specifically directed at relaxed static stability and lower frequency effects. The dominance of compensation lead (ϕ_{PL}) is evidenced by the near vertical slope of the iso-rating lines, especially for the worst cases (Level 3 boundary). The cut-off of the Level 2 boundaries, at about RA = 9, is somewhat arbitrary as the line is the Level 2 boundary from Neal and Smith (Ref. 7) which has a somewat different basis. Neal and Smith give no Level 3 boundary.

BW = 3 rad/sec. The criteria at BW = 3 rad/sec are notable for several characteristics. The range of lead (ϕ_{PL}) and resonant amplitude (RA) covered by the data was quite small, and the Level 3 boundary (PR = 8.5) below $\phi_{PL} = 100^{o}$ results from extrapolation. The iso-rating lines are nearly horizontal, so the dominant factor is resonant amplitude. The Neal-Smith (Ref. 7) Level 2 boundary, when simply extended to larger lead, falls above the indicated Level 3 boundary. The criteria at BW = 3 rad/sec are specifically directed at higher frequency effects such as may result from control system, feel system, and other higher-order characteristics. However, the simulator data (App. B and C) do not embrace significant higher-order characteristics. There was some evidence of higher frequency resonance (5 to 7 rad/sec) in the analytical loop closures which was also mildly evident in the time history data. Feel system and control system dynamics for most of the simulator configurations were good (fast and well damped), selected to duplicate the LAHOS baseline ones of Smith (Ref. 8). However, the analytical closures did indicate that moderate deterioration in the feel system or actuator would have precipitated severe resonance at the higher frequencies. Considerable thought was given as to whether the iso-rating lines for the BW = 3 rad/sec closure should be used as criterion boundaries for Level 2 and 3. Alternatives were to extend and use the Neal-Smith (Ref. 7) Level 2 boundary, to use Chalk's (Ref. 23) Level 2 boundary of RA = 9 db (3 db for Level 1), or simply to note the need for boundaries as yet to be determined. The criterion Level 2 and 3 boundaries for BW = 3 rad/sec, as shown on Fig. 4, are included as requirements based on the following logic and argument.

The Level 2 and 3 boundaries as shown on Figure 4 are conservative as compared to the Neal-Smith (Ref. 7) and Chalk (Ref. 23) boundaries. However, the data upon which the boundaries in Figure 4 are based indicated that moderate deterioration in feel system and actuator characteristics, as described above, would have precipitated high frequency oscillations or PIO's. Had such deterioration occurred, then pilot ratings for the given configurations would have been rated worse, perhaps

7 or 7.5, while an 8.5 configuration on the Level 3 boundary might have gone to a 9 or 10. In effect, it is judged that the criterion boundaries for BW = 3 rad/sec need to be more stringent for airplanes with relaxed static stability than for stable ones because the effects of deterioration in flying qualities, at higher frequencies (3 rad/sec) due to higher order dynamics and at lower frequencies (1 rad/sec) due to relaxed static stability, are cumulative. Accordingly, the Level 2 and Level 3 boundaries for BW = 3 rad/sec, as shown on Figure 4, have been set at the PR = 6.5 and 8.5 iso-rating lines of the simulator data (App. B). Verification of this assumption, and the BW = 3 rad/sec Level 2 and 3 boundaries in Figure 4, is desirable. Such verification will require, for various levels of relaxed static stability, that pilot rating data be obtained for the deleterious (cumulative) effects of higher order dynamics. Until such additional data is available, the boundaries shown in Figure 4 are recommended to protect against high frequency oscillations (PIO's) and loss of control.

The cut-off indicated for Level 2 and Level 3 boundaries at $\phi_{PL} = 125^{\circ}$ (Fig. 4, BW = 3 rad/sec) derives from two considerations. First, the compensation model, as prescribed in the criteria, allows at most a $\phi_{PL} = 135^{\circ}$ with $1/\tau_{p_3}$ = BW. But, $\tau_{p_1} \rightarrow \infty$ as $\phi_{PL} \rightarrow 135^{\circ}$, and when $1/\tau_{p_1}$ becomes too small, then the low frequency characteristics become badly distorted as do the conditions for calculating the required compensation. Secondly, no configurations upon which the BW = 3 rad/sec criterion was based had $\phi_{PL} > 115^{\circ}$. The $\phi_{PL} = 125^{\circ}$ cut-off required only minor extrapolation and avoids the analytical difficulty with small $1/\tau_{p_1}$. If the analytical technique ever needs to be extended to $\phi_{PL} > 125^{\circ}$, then further theoretical development would be required, but, as shown in Appendix B, Section B.6.1.3, a moderate decrease in $1/\tau_{p_3}$ would not change the results significantly and would allow somewhat larger ϕ_{PL}.

Control system sensitivity. The frequency response criteria do not include or impose any requirements upon contol sensitivity, $M_{\delta_{ES}}$ or M_{F_S}, despite the fact that compensation or pilot gain (K_p) is one of

the parameters adjusted to meet the closed-loop performance criteria. Accordingly, the requirements on control sensitivity as given for the parametric criteria apply also to the frequency response criteria, including the applicable range shown in Figure 1 and the correction shown in Figure 3 for low sensitivity.

Though only a very minimum investigation of control sensitivity, just two levels, was made on the simulator (App. B), the results show the importance of sensitivity for relaxed static stability. The pilot rating decrement in Figure 3, just the difference for the two levels, shows significant degradation in flying qualities for the lower level of sensitivity. The pilot rating correction of Figure 3 was applied to the ratings for all configurations with low sensitivity and relaxed static stability, and then plotted with the high sensitivity rating data on the RA vs. ϕ_{PL} plane of Figure 4. The correlation was excellent (Fig. 17). It should be noted that the ratings used to generate Figure 3 were for configurations where the only difference between pairs was the two values of $M_{\delta_{ES}}$, whereas the correlation in the RA vs. ϕ_{PL} plane included substantially different configurations in the satisfactory and low $M_{\delta_{ES}}$ sets. Thus, the use of the Figure 3 correction to correlate data in the RA vs. ϕ_{PL} plane was not just a meaningless reverse processing. Rather, it provides a gratifying independent check on the validity of the criteria in Figures 3 and 4. If the correction of Figure 3 for low $M_{\delta_{ES}}$ is to be applied directly to the frequency response criteria of Figure 4, then the iso-rating lines in the RA vs. ϕ_{PL} plane provided in the supporting data must be used to obtain pilot ratings, which should then be corrected for low $M_{\delta_{ES}}$ and converted to flying qualities Level.

Other Flight Phases.

Rationale for extension of the parametric and frequency response criteria from approach and landing to other flight phases is based on several assumptions: (1) relaxed static stability poses primarily a pitch attitude control problem, (2) criteria which adequately define limits on the pitch attitude to pitch control transfer function, θ/F_S, will provide valid requirements for relaxed static stability, (3) the

requirements are task dependent, and (4) the dependency is defined by the precision with which the pilot controls attitude and the extent to which he can or will devote attention to attitude.

On this basis, all Category A and those Category C tasks requiring precise attitude control would have similar requirements. The applicable ranges of the parameters in the parametric criteria, in themselves, limit application to appropriate Category A and C flight phases and flight conditions. The frequency response criteria, on the other hand, are sufficiently general that they ought to apply to all these flight phases and conditions.

For Category B fight phases and those Category C flight phases not requiring precise attitude control, the pilot needs to control attitude only enough to contain the instability when it is present. This is a low bandwidth task, and a bandwidth of 1 rad/sec provides more than adequate control. Difficulty in these flight phases will come from fatigue caused by the need for continuous control over long periods of time, or from the need to divert attention from attitude control to other necessary tasks. On this basis, the frequency response criteria of Fig. 4 for BW = 1 rad/sec seem reasonable requirements for the short term. For the long term, defined somewhat arbitrarily as in excess of 10 minutes, more stringent Level 3 requirements for BW = 1 rad/sec are imposed (i.e., same as Level 2). If a failure leads to Level 3 flying qualities, then 10 minutes is allowed to reconfigure the airplane or change flight conditions to one where the airplane may be flown to a destination with at worst Level 2 flying qualities.

The requirement, for contractor demonstration by simulation of Level 2 and Level 3 flying qualities under conditions where the pilot has additional duties and responsibilities, has been imposed in recognition that these additional duties and responsibilities are very much dependent on the specific aircraft design and mission requirements. It is necessary to ensure, in each individual case, that the additional work load placed on the pilot does not seriously detract from his ability to

control attitude under failure conditions which result in relaxed static stability. If they do, then the pilot's work load must be reduced, or the flying qualities improved.

Long Period Oscillation

If the frequency response requirements are met, the long period or phugoid oscillation should be taken care of as well as the short period. However, since the parametric criteria impose no restriction on the long period oscillation, some restriction is needed for these criteria to apply. The recommended restriction ensures that the phugoid roots will be near the origin and stable.

Since there is no flight test method for determining long period oscillation characteristics in the presence of relaxed static stability, demonstration of compliance must be analytical, based on estimates of the roots. However, stability derivatives can be determined from flight test for comparison with the values used in the analytical prediction, and time history comparisons can be made which will expose gross differences.

Pilot Induced Oscillation

Rationale for the relaxed requirement on pilot induced oscillations is based on the results of the simulator investigation (App. B). Time histories clearly showed low frequency sustained oscillations for all cases of relaxed static stability. Pilot ratings and comments indicate that the frequency and amplitude of these oscillations, and the degree the pilot could control them, were an important factor in his assigning of a rating. For the better configurations, the pilot saw "no PIO tendency". For the worse configurations, the pilot noted "a strong PIO tendency". The pilot controls attitude with some threshold, so with an unstable airplane there will be a limit cycle or a sustained oscillation. In effect then, a PIO tendency is an inherent aspect of relaxed static stability. The modified requirements, allowing a PIO tendency, reflect the pilot assessment of it. The 3 rad/sec upper limit comes from the frequencies corresponding to the resonances in the data upon which the closed-loop frequency requirements of Figure 4 are based.

Flight Path Stability

All the data upon which the requirements for relaxed static stability of Figures 1 through 4 are based had front-side characteristics, i.e., $d\gamma/dV < 0$. Positive values of $d\gamma/dV$ tend to degrade flying qualities, and MIL-F-8785C (3.2.1.3) requires $d\gamma/dV \leq 0.06$ deg/knot for Level 1. Wasserman and Mitchell (Ref. 24) found only a slight degradation in flying qualities for $d\gamma/dV = +0.069$ deg/knot compared to $d\gamma/dV = 0$. This was found for relaxed static stability configurations with $T_2 = 2$, 4 and 8 seconds. The Level 1 requirement of MIL-F-8785C of $d\gamma/dV = 0.06$ deg/knot is recommended for Level 2 and Level 3 in the presence of relaxed static stability, on the basis that no additional degradation in flying qualities can be allowed due to back-side operation.

The rationale for a requirement on $d\gamma/dV$ appears to rest primarily upon its relation to the small numerator of the γ/δ_e or h/δ_e transfer function, $Z_{h_1} = -1/T_{h_1}$ (Ref. 2, 3.2.1.3):

$$Z_{h_1} = -1/T_{h_1} = g \frac{d\gamma}{dV}$$

Though several derivations or interpretations exist of how this zero enters into the piloting task (see Ref. 2, 3.2.1.3; Ref. 24, App. II; Ref. 25, App.E; Ref. 26, 2.3.3), they all depend on the pilot closing some form of altitude loop with the pitch control, generally in addition to an attitude closure. Assuming that the pilot uses an inner loop attitude closure to control on altitude, we may write the transfer function for h/θ_c as follows.

$$\frac{h}{\theta_c} = \frac{\theta}{\theta_c}\,\frac{h/\delta_e}{\theta/\delta_e} = \frac{\theta}{\theta_c}\,\frac{A_h(s - Z_{h_1})(s - Z_{h_2})(s - Z_{h_3})}{A_\theta s(s - Z_{\theta_1})(s - Z_{\theta_2})}$$

Generally Z_{h_2} and Z_{h_3} will be large and of opposite sign, Z_{θ_2} will be large and negative, and Z_{h_1} will be small and positive or negative depending on $d\gamma/dV$. Assuming that only low-frequency characteristics are of interest, and that $\theta/\theta_c=1$ in the attitude closure, we may write the following approximation for h/θ_c for low frequencies. (Note: A_h and A_θ must be redefined so low frequency gains will be equal in the two transfer functions.)

$$\frac{h}{\theta_c}(s) \approx \frac{A_h(s-Z_{h_1})}{A_\theta(s-Z_{\theta_1})}$$

It is obvious that closing h/θ_c will lead to a root near Z_{h_1}, and if Z_{h_1} is in the right half plane (Z_{h_1} positive, $d\gamma/dV$ positive, back-side), then there will always be an unstable root with tight altitude closure.

Thus the problem with positive $d\gamma/dV$ is that it causes $Z_{h_1} = -1/T_{h_1}$ to be positive and leads to instability if the pilot tries to control flight path angle or altitude with pitch control. Divergence occurs in airspeed, angle of attack and attitude, also altitude depending on how tight the loop is closed. An airspeed closure with throttle by pilot or auto-throttle will eliminate the instability (given attitude stabilization).

Though positive $d\gamma/dV$ may create problems for the pilot under any circumstances where the angle of attack is large and the pilot must control flight path (e.g., takeoff, cruise, high altitude maneuvering, refueling), quantitative data on requirements are only available for the landing approach where the problem is most critical.

D. GUIDANCE FOR APPLICATION

The essence of the requirements for relaxed static stability, those on control power excepted, are contained in this paragraph 3.2.1.3. The requirements are stated in two forms, a parametric one and a frequency response one, with overlapping ranges of applicability and differing degrees of difficulty in application. Both are based on the same flying qualities data. Most importantly, both criteria scrap the old criterion of 6 seconds time to double amplitude (T_2), replacing it with criteria which will allow T_2 as short as 2 sec, while guarding against unsafe flying qualities that can occur with T_2 of 6 sec or longer, or even for stable configurations.

These criteria scrap the fallacious notion that relaxed static stability, as realized by aft c.g. location, results in a speed instability. The instability is one of attitude response with speed only a secondary effect. These criteria are essentially failure state criteria, meant to be applied to unaugmented aircraft or ones with

back-up, hard, or essential SAS to retain flyability in all probable Failure States.

Parametric Criteria

The parametric criteria, a direct functional expression of the flying qualities data for approach and landing in terms of airplane parameters, are intended as simple criteria suitable for use in preliminary design as well as final criteria. Because of their form, the range of application is limited to the ranges of parameters represented in the criteria as shown in Figures 1 through 3. Though strictly limited to the approach and landing task, they should be applicable to any task which requires precise control of flight path and where the criteria parameter ranges are applicable. Because the criteria of Figures 1 through 3 only cover the short period roots (λ_{sp_1}, λ_{sp_2}), large zero ($Z_{\theta_2} = -1/T_{\theta_2}$) of the θ/F_S transfer function, and control sensitivity ($M_{\delta_{ES}}$), additional restrictions are imposed on phugoid frequency and damping and flight path stability ($d\gamma/dV$).

Frequency Response Criteria

The frequency response criteria, an extension of the Neal-Smith criterion (Ref. 7), are intended to cover a broad range of characteristics from phugoid motions to actuator dynamics, including higher order effects associated with the flight control system. The frequency response criteria are for attitude control, and are pertinent to the frequency band of interest to the pilot in controlling attitude, considered to be from .1 rad/sec to 10 rad/sec. Above 10 rad/sec, airplane characteristics can be objectionable to the pilot, as uncontrollable vibrations, but they are not part of flying qualities. Below .1 rad/sec, the pilot is not concerned with attitude but rather with airspeed, flight path, and altitude. These he controls with throttle, or a combination of throttle and pitch control. Thus the very low frequency ($\omega < 0.1$ rad/sec) characteristics of the attitude response are not significant and need not be included in the attitude response criteria. For low frequencies, the response of speed and flight path to throttle inputs, possibly combined throttle and pitch control inputs, would be germane. However, the problem posed by relaxed static

stability is one of attitude control, and appropriate criteria on the frequency response of attitude to pitch control (θ/F_S transfer function) for $0.1 < \omega < 10$ rad/sec should adequately treat the problem.

The frequency response criteria are applied for two bandwidths, BW = 1 rad/sec and 3 rad/sec, on the basis that the airplane must have satisfactory characteristics over the range of bandwidths the pilot may use. Ideally, the criterion would be a continuous function of bandwidth, but two discrete values are used on the basis that they will suffice. Each covers different aspects of the problem. The lower bandwidth (BW = 1 rad/sec) is the one that primarily deals with the effects of relaxed static stability. The higher bandwidth is directed more at control system and higher order effects.

The key to understanding the frequency response criteria is recognition that they involve the amplitude and phase of the open-loop response of the airplane. Flying qualities (Levels or pilot rating) are evaluated in terms of the phase angle at two frequencies (1 and 3 rad/sec) and the shape of the open-loop frequency response. However, the criteria, in terms of the phase angle and shape, involve a fairly complex process derived from closed-loop pilot-vehicle analysis concepts. The easiest way to understand this is to view the response on a Nichols chart (Fig. 5), a plot of open-loop amplitude (db) vs. phase.

Three open-loop frequency responses are shown on Figure 5 for the example case, Configuration L72 of the simulator investigation (App. B), which with minor differences is Smith's LAHOS Configuration 7-2 (Ref. 8). The uncompensated open-loop response of θ/F_S has an added gain (about 45 db) to bring it to a convenient level with 3 rad/sec at 0 db. The compensated responses have Y_p added to θ/F_s, with Y_p determined from the criteria for BW = 1 and 3 rad/sec. On Figure 5 are also plotted curves of constant closed-loop amplitude and phase, where closure is with unity feedback and a forward loop gain as specified in the criteria.

The compensated responses, for the example case in Figure 5, have a closed-loop (θ/θ_c) minimum (for $0.1BW < \omega < BW$) or "droop" at $\omega = BW$, so the curves go through the intersection of the 0 db and -90^0 closed-loop curves. The criterion phase angle is the phase

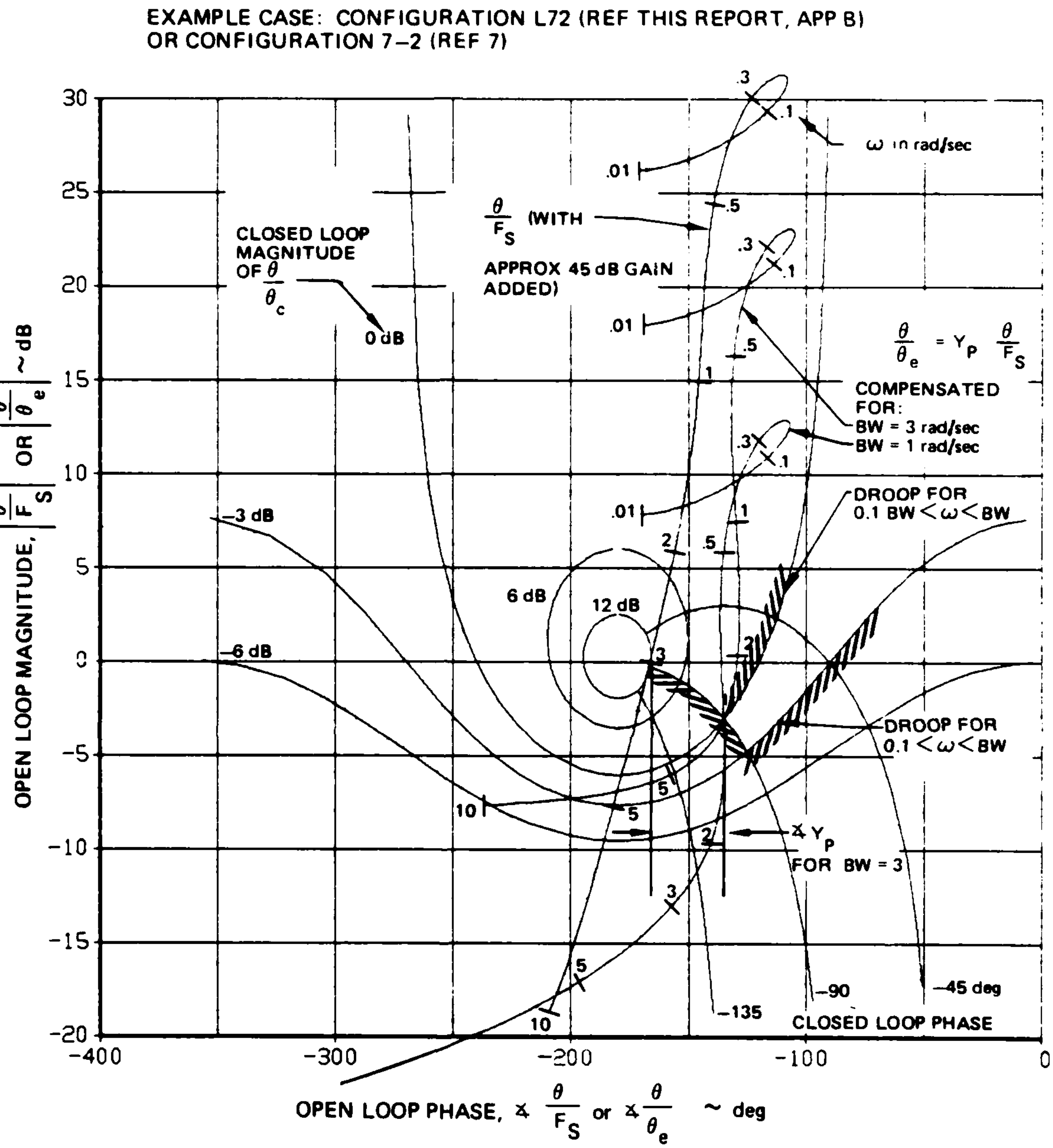


Figure 5 (3.2.1.3). Example Application of RSS Frequency Response Criteria Using Nichols Chart

of Y_p without the time delay, evaluated at the bandwidth frequency, and computed as follows:

$$\phi_{PL} = \measuredangle Y_p(\omega = BW) + 0.3(57.3)\ BW$$

The phase of Y_p may be measured directly on Figure 5, and is the open loop phase (lead) from the 1 and 3 rad/sec points on θ/F_S to the intersection of the compensated curves and the -90^o closed-loop curve (also the 0 db curve in this case). The $\measuredangle Y_p$ is 11^o for BW = 1 and 31^o for BW = 3, and using the above equation gives ϕ_{PL} = 28 degrees and 83 degrees for BW = 1 and 3 rad/sec, respectively. The pilot model must add enough lead to overcome the 0.3 sec. time delay as well as provide 11^o or 31^o phase advance.

The shape of the open-loop frequency response is evaluated by adding the required compensation (Y_p) and determining the closed-loop resonant amplitude, RA. This can be done directly on the Nichols chart from the curves of constant closed-loop amplitude, as in Figure 5. For the example, resonance occurs at about 0.6 rad/sec with RA = 3 db for BW = 1, at about 1.3 rad/sec with RA = 2 db for BW = 3. Though RA is the closed-loop resonance, it is determined from lines of constant RA on the Nichols plot of open-loop amplitude vs. phase. The flying qualities Level is then evaluated by plotting RA and ϕ_{PL} for each case on the criterion plots of Figure 4.

The key process in applying the criteria is determining Y_p. This can be done graphically using Nichols charts. First the frequency response of the invariant parts, $e^{-0.3s}(\tau_{p_3}s+1)\frac{\theta}{F}(s)$, is plotted on the Nichols chart. Then K_p and τ_{p_1} are adjusted (since almost invariably $\tau_{p_2} = 0$ for RSS) for the "droop" = 0 db condition, checking that the "droop" $\geq$ -3 db condition is not violated. The process is simple when 0 db "droop" occurs at BW, as it usually does for RSS. In this case τ_{p_1} is set so that $\measuredangle(\tau_{p_1}s + 1)$, evaluated at ω = BW, is just the difference between the phase of the invariant parts at ω = BW and -135^o, the phase angle of the intersection of 0 db and -90^o curves; K_p is set to put BW on this intersection. If 0 db droop occurs below BW, then further adjustment is required. The graphical technique, done by hand, becomes tedious if many cases are to be run, and

use of a digital computer program is recommended. The program by Mayhew, described in Reference 27, works well for the standard Neal-Smith criteria as well as the RSS criteria. However, even though a computer program is used for all calculations, the Nichols chart with its closed-loop contours is still recommended as the best way to view the results.

The frequency response criteria are intended to apply to any aircraft exhibiting static instability or near neutral stability, or any airplane that fails to meet the Level 1 short period requirements for Category C Flight Phases of MIL-F-8785C (3.2.2.1.1) because short-period frequency is too low. The following test may be applied. Perform the attitude loop closure at BW = 3 rad/sec, but with $\tau_{p_3} = 0$, adjusting K_p, τ_{p_1} and τ_{p_2} for minimum RA instead of ϕ_{PL} (which normally results in droop of -3 db rather than 0 db). That is, perform a standard Neal-Smith closure. If $\phi_{PL} > 80^o$, then the RSS criteria with $\tau_{p_3} = 1/BW$ should apply instead.

Because the frequency response criteria place no requirements on control sensitivity, the parametric criteria requirements for control sensitivity must be used in conjunction with the frequency response criteria. When $M_{\delta_{ES}}$ falls below the acceptable range ($.25 \le M_{\delta_{ES}} \le .55$ rad/sec^2/in) and the effect on flying qualities Level needs to be determined, then Figure 3 may be used to estimate the degradation in pilot rating which is applied as a correction to the iso-rating data found in the supporting data (Figures 16 and 18). This net rating is then converted to a Level.

Other Flight Phases and Requirements

Extension of the approach and landing data to other flight phases has been made. Also requirements have been imposed on phugoid dynamics (ζ_p, ω_{n_p}) and flight path stability ($d\gamma/dV$) without full knowledge of their interaction with relaxed static stability. PIO requirements have been relaxed, qualitatively. The extended requirements as stated are heavily influenced by judgement. All of these are areas of uncertainty, and extensive use of ground simulation, augmented by in-flight simulation if possible, should be made in any specific design to ensure that flying qualities reflect the intent of the Level 2 and 3 requirements.

G. DEMONSTRATION OF COMPLIANCE

Flight test results should be used to verify the data base for calculating the parameters (e.g., roots) in the criteria. Parameter identification may be used to extract basic airplane derivatives from flight tests of the stable augmented airplane if the right quantities are measured. Flight test data may also be used to obtain frequency responses of θ/F_s, or describing functions if nonlinear effects are present, which may be used in the criteria directly or used to verify analytically calculated responses. Final verification of the suitability of the achieved flying qualities must come from pilot evaluations in flight test. But caution must be used because of the danger involved if predicted flying qualities for the Failure States turn out to be optimistic.

The requirements for relaxed static stability are stated primarily in analytical terms, and compliance must accordingly be demonstrated by analysis of data. Flight testing for the characteristics and parameters used in the criteria may be difficult, possibly dangerous. With instability present, trim conditions are hard to establish and the unstable divergence can mask sought for characteristics in transients.

Extensive ground simulation should be used to demonstrate compliance with the intent of the requirements, and to verify appropriate Levels of flying qualities. If at all possible, in-flight simulation should be used to check and validate the results of the ground simulation, especially in takeoff and landing and any conditions critical to flight safety. Recent experience (Ref. 43 and 44) has shown that ground simulators cannot be trusted to predict PIO tendencies correctly. Severe and dangerous conditions, not detected in the ground simulator, have been encountered during in-flight simulation of specific aircraft with variable stability aircraft, fortunately prior to first flight (Ref. 43). This disparity should not apply to the simulation results on wnich the RSS criteria are based since the PIO's described above were higher in frequency ($\omega > 3$ rad/sec) than the oscillations associated with RSS ($\omega < 3$ rad/sec), and most importantly, the simulation results are supported by flight test data.

H. SUPPORTING DATA

A search for flying qualities data pertinent to criteria for relaxed static stability reveals that there is not a large amount of data. The BIUG for MIL-F-8785B (Ref. 2) lists five reports containing flight data on static instability, References 26, 28, 29, 30 and 31. The F-94 data by Chalk (Ref. 29) and the F-86 data by McFadden (Ref. 30) were from fighter evaluations made at altitude, and neither used Cooper-Harper pilot ratings. The B-26 data by Bull (Ref. 28) was from landing approach evaluations covering a wide range of short-period frequencies and dampings, and even though it did not use the Cooper-Harper scale, the results are considered significant and useful. The T-33 data by Chalk in Reference 31 contain only one unstable configuration, and those in Reference 26 contain only two unstable configurations, both phugoid instabilities.

Since publication of the BIUG (Ref. 2), two additional flight investigations have been reported containing significant data for the approach and landing, the work of Wasserman and Mitchel (Ref. 24) and that of Smith (Ref. 8). These, together with Bull's work (Ref. 28), comprise the bulk of the data on approach and landing flying qualities applicable to minimum stability requirements for airplanes with relaxed static stability.

Besides the flight data cited above, three airplane programs have involved the use of RSS: (1) the U.S. Supersonic Transport program with its initial Boeing SST development (cancelled) and subsequent NASA supported studies, (2) the Anglo-French (SNIA/BAC) Concorde SST, and (3) the YF-16 and F-16 airplanes. Results from the Boeing SST development are summarized by Kehrer (Ref. 14 and 15) and Tomlinson (Ref. 32). Much of the pertinent SST data from NASA studies and the Concorde are summarized by Chalk (Ref. 23). An SST simulation study performed by Sudderth et al. (Ref. 22) contains data on minimum stability and stall recovery requirements.

More recently Kehrer (Ref. 16) considers the application of RSS to advanced tactical aircraft and the requirements on stability, controllability and angle-of-attack limiting.

As for data with respect to the RSS requirements from the YF-16 and F-16 programs, since the airplanes are fly-by-wire and always have stability augmentation on, no data seems to have been generated concerning minimum stability levels.

Flying qualities data applicable to minimum requirements for RSS airplanes must essentially come from simulator investigations, either ground based, or in-flight with variable stability airplanes where reversion to a non-catastrophic situation is possible.

Criteria Coordinates

Criteria developed in past investigations for the minimum levels of allowable stability (maximum instability) for safe operation have mostly been in terms of the time to double amplitude of the airplane's response, usually calculated from the unstable root (λ_1) of the three degrees of freedom characteristic equation as follows:

$$T_2 = \ln 2/\lambda_1 = .693/\lambda_1$$

Available data of this type is summarized in Appendix B, Section B.3.1.

Alternatively, boundaries have been drawn in the ω_n^2 vs $2\zeta\omega_n$ plane where ω_n^2 and $2\zeta\omega_n$ are the coefficients in the quadratic defining the short period mode as follows:

$$s^2 + bs + a = 0$$
$$b = 2\zeta_{sp}\omega_{n_{sp}} = -(\lambda_{sp_1} + \lambda_{sp_2})$$
$$a = \omega_{n_{sp}}^2 = \lambda_{sp_1}\lambda_{sp_2}$$

The advantage of the ω_n^2 vs $2\zeta\omega_n$ coordinates is that they allow plotting of all possible values of the short period roots, stable or unstable, oscillatory or real. Also the MIL-F-8785C short period requirements can be plotted, with n/α as a parameter, on these coordinates.

The parametric criteria for relaxed static stability (RSS) as recommended use the real roots (λ_{sp_1}, λ_{sp_2}) as coordinates for one of the primary criteria. This set of coordinates was selected as the most appropriate for RSS cases, though oscillatory short periods and the

MIL-F-8785C requirements in toto cannot be plotted on them. The λ_{sp_1} vs λ_{sp_2} coordinates can be transformed to the ω_n^2 vs $2\zeta\omega_n$ plane using the following parametric equations,

$$a = \omega_n^2 = -\lambda_1 b - \lambda_1^2$$
$$b = 2\zeta\omega_n = -\lambda_1 - \lambda_2$$

where λ_{sp_1} and λ_{sp_2} can be either λ_1 or λ_2. The transformation is illustrated in Figure 6. It can be seen that all real roots fall below the $\zeta = \pm 1$ parabola. Iso-root (constant values of a root) lines are straight lines, all of the same family, with $2\zeta\omega_n$ intercept at $-\lambda_1$ and slope of $-\lambda_1$. The area of interest for RSS is the right half plane, near or below the $2\zeta\omega_n$ axis. Above this is the area of primary interest to the normal (MIL-F-8785C) short-period requirements. Real root combinations (λ_{sp_1} and λ_{sp_2}) are defined by the intersecting iso-root lines at any point. With the transformation shown in Figure 6, the criteria requirements from Figure 1 can be plotted on the ω_n^2 vs $2\zeta\omega_n$ plane together with the available flight test data and the short period requirements from MIL-F-8785C, 3.2.2.1.

Comparison of Criteria and Flight Test Data

The most significant flight test data relative to RSS requirements are the approach and landing data of Smith (Ref. 8), Wasserman and Mitchell (Ref. 24), and Bull (Ref. 28). Appendix B, Section B.3 of this report provides a summary of the available ground simulation and flight test data, describes why the aforementioned data comprise the bulk of useful data, describes each flight program briefly, and presents the data most pertinent to RSS on a plot of ω_n^2 vs $2\zeta\omega_n$ together with the appropriate MIL-F-8785C short-period requirements (Figure B-14). These data are compared on Figure 7 with the requirements from Figure 1 for moderate turbulence. The agreement is generally good. More detailed considerations follow, with the following designations used to identify the data:

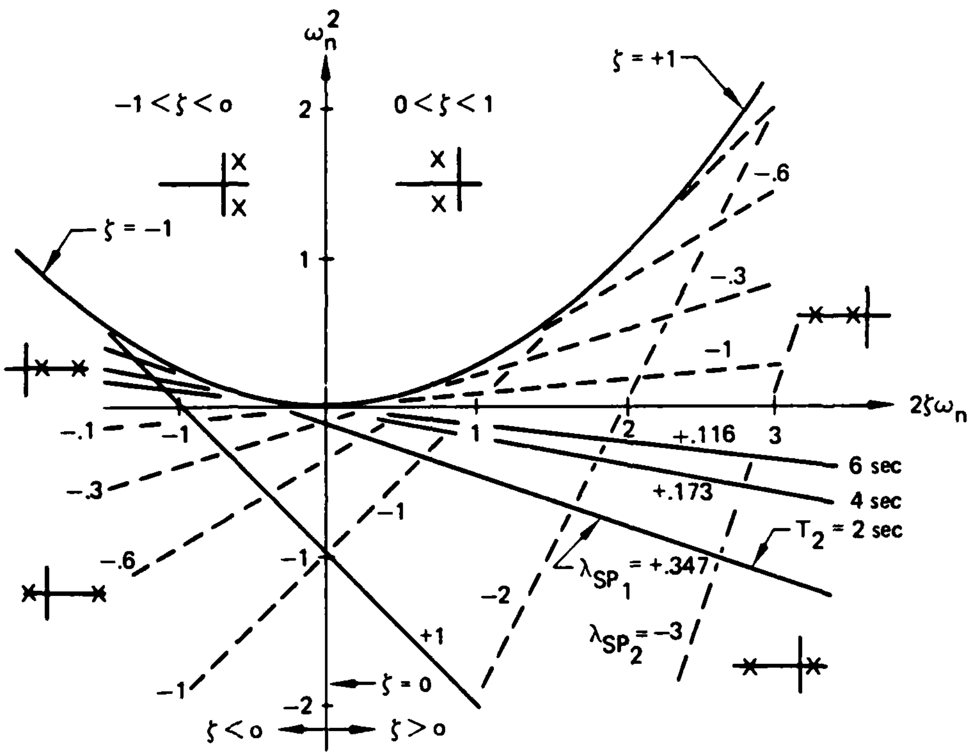


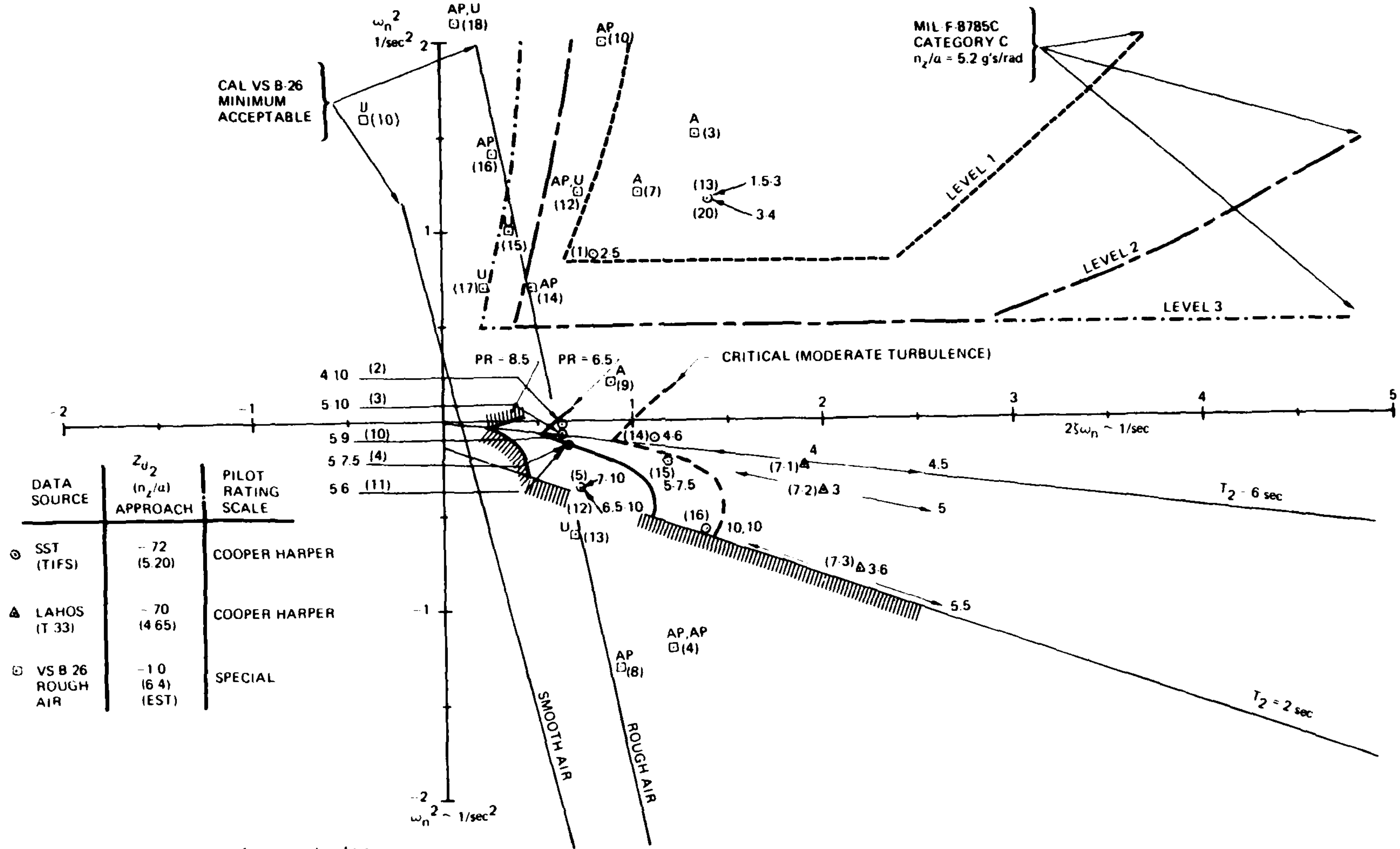
Figure 6 (3.2.1.3). Relation of Real Roots (λ_{SP_1}, λ_{SP_2}) to ω_n^2 vs $2\zeta\omega_n$ Coordinates

SST	Wasserman and Mitchell (Ref. 24)
LAHOS	Smith (Ref. 8)
B-26	Bull (Ref. 28)

In overview, the RSS criteria requirements and iso-rating (constant pilot rating) lines are for $Z_{\theta_2} = -0.6$, a desirable level of control sensitivity, and moderate turbulence. The LAHOS data closely duplicates these conditions. The SST data had for the RSS cases a very low control sensitivity ($M_{\delta_{ES}} = 0.18$ rad/sec^2/in, $M_{F_S} = .09$ deg/sec^2/lb) which, based on the data of Figure 3, should have degraded pilot rating by a $\Delta PR = 2$ or more, especially the worst configurations. The spread in pilot rating for the SST configurations generally reflects the effects of turbulence (measured by total rms gust velocity, σ_V), with the better ratings in light turbulence ($\sigma_V < 1.5$ fps) and poorer ratings in moderate turbulence ($\sigma_V < 3$ fps). The B-26 data have a somewhat large value of Z_{θ_2} which, based on Figure 2, should have degraded pilot rating about a $\Delta PR = 1$. No data is given on control sensitivity. The B-26 pilot ratings used a special scale, not Cooper-Harper, and were in terms of acceptability for emergency conditions after a stability augmentation system failure or malfunction. Approaches were made using a mirror landing system and not an ILS system. Flights were generally in two intensities of turbulence, smooth air (over water) or moderate turbulence called "rough air" (northeastern U.S. summer weather, over land).

Referring to Figure 7, the LAHOS data agree well with the criteria pilot rating values, with the pilot rating of 3 (moderate turbulence) for Config. 7-2 being somewhat better than the criteria PR = 5.

The SST data for Config's 2, 3, 10, and 4 have an average PR $\simeq$ 6.5, and thus agree well with the PR = 6.5 iso-rating line, with Config. 11 slightly better. These config's have the lowest value of λ_{sp_2} (see Fig. 6) and would be degraded least by the low sensitivity ($M_{\delta_{ES}}$). Config's 5 and 12 have an average PR $\simeq$ 8.5, which is one rating lower than the PR = 7.5 indicated by the iso-rating lines, again consistent with the low $M_{\delta_{ES}}$. Config's 14 and 15 have average PR the same as or better than the iso-rating lines. Configuration 16, however, has ratings substantially worse (PR = 10) than the PR = 5.5 indicated by the



( ) No's in parentheses are configuration identifiers.

Numbers beside points are Cooper Harper pilot ratings. B 26 A = Acceptable, AP = Acceptable Poor, U = Unacceptable.

Commas indicate a repeat. Range is shown (e.g., 6.5 10) for multiple rating or repeats.

Figure 7 (3.2.1.3). Flight Data on Minimum Longitudinal Stability and Criteria Boundaries, ω_n^2 vs $2\zeta\omega_n$

iso-rating lines. This configuration had the largest λ_{sp_2} (-1.6), so the degradation due to low $M_{\delta_{ES}}$ would be the greatest ($\Delta PR > 2$). Two evaluations were made of Config. 16; both received heavy "turbulence effects ratings" (E and F, moderate and major increase in pilot effort due to turbulence, respectively); but measured turbulence was not severe (σ_v = 2.5 fps for the E rating, and even less, σ_v = 1.0 fps, for the F rating). The stable configurations (1, 13, 20) have pilot ratings in agreement with the normal Level 1 boundaries; they also had twice the control sensitivity ($M_{\delta_{ES}}$) of the RSS configurations. No explanation is given for why the RSS cases had lower sensitivity. It is felt that the low $M_{\delta_{ES}}$ was responsible for the PR = 10 for Config. 16, also most of the 10 ratings for other configurations and the large resultant rating spread (e.g., Config. 2 rated from 4 to 10).

The B-26 data, using a scale different from the Cooper-Harper one, cannot be compared directly in terms of pilot rating. Data points are given in Figure 7 only for the "rough air" (moderate turbulence) evaluations. However, Bull's (Ref. 28) fairing of the data for minimum acceptable flying qualities for both smooth and rough air are given. If these are considered PR = 8.5 boundaries, and a one rating point degradation is allowed for the larger Z_{θ_2}, then the rough-air boundary would move to the left the equivalent of one rating point and agree very well with the PR = 8.5 iso-rating line of the criteria. The B-26 data points show good agreement with the MIL-F-8785C Level 1, 2, and 3 boundaries above $\omega_n^2 = 0.5$. Acceptable (A) ratings are Level 1, acceptable poor (AP) ratings are generally Level 2 or 3, and unacceptable (U) ratings fall to the left or outside the Level 3 boundary. Viewing the ratings for lower ω_n^2 (< .5), Configuration 9 with an A rating is well below the Level 3 boundary, and suggests that a constant $2\zeta\omega_n$ boundary might be appropriate for extending the PR = 8.5 and PR = 6.5 RSS criteria boundaries above $\omega_n^2 = 0$. Configurations 4 and 8 have $\lambda_{sp_1} \simeq +0.8$ or $T_2 \simeq 0.9$ sec (see Fig. 6), and their acceptable poor (AP) ratings indicate that the RSS criteria boundaries (PR = 8.5, PR = 6.5, critical) may well extend down along constant λ_{sp_2} lines (see Fig. 6) much farther than $\lambda_{sp_1} = +.35$ ($T_2 \simeq 2$ sec). Config. 13, allowing for the equivalent one pilot-rating shift to the left, confirms the general shape of the RSS criteria boundaries.

In summary, the SST (Ref. 24), LAHOS (Ref. 8) and B-26 (Ref. 28) flight data confirm and correlate well with the RSS criteria boundaries for Level 2 (PR = 6.5) and Level 3 (PR = 8.5), excepting SST Configuration 16. This exception may be explained on the basis of its very low control sensitivity ($M_{\delta_{ES}}$), but it is still viewed as a somewhat anomalous data point. It is important to note that, though the LAHOS data was used as part of the basis for the derivation of the RSS criteria in that the three LAHOS configurations were simulated in the underlying ground simulation program, the comparison with SST and B-26 data is completely independent and after the fact of the RSS criteria derivation.

Simulation Data Basis for Criteria

The RSS criteria of Figures 1, 2 and 3 are directly based on the results of the fixed base ground simulation of approach and landing described in Appendices B and C. The baseline characteristics were those of the F-111A. The piloting task was comprised of inbound instrument flight at altitude, localizer and glide slope acquisition, maintenance of glide slope to break-out at 200 ft. altitude, visual short final to flare and semi-precision (between 1000 and 2000 foot markers) touchdown. Each evaluation included three levels of turbulence (*negligible*, *moderate*, severe) and a 150 foot lateral offset (random direction) from runway on break-out. The three pilots were experienced Boeing test pilots, two with recent fighter experience. Ground simulation was used to develop the criteria because there was no other source of flying qualities data with consistent and independent variation of parameters in the θ/F_s transfer function. This transfer function was felt to be the key to understanding and developing valid criteria for relaxed static stability.

The θ/F_s transfer function can be written in the following form:

$$\frac{\theta}{F_s} = Y(s)_{cs} \frac{A_\theta (s - Z_{\theta_1})(s - Z_{\theta_2})}{(s - \lambda_{sp_1})(s - \lambda_{sp_2})(s^2 + 2\zeta_p \omega_{n_p} s + \omega_{n_p}^2)}$$

The short period roots are real, with λ_{sp_1} selected as the most unstable root, smaller in magnitude than λ_{sp_2}. The phugoid will generally have oscillatory roots, but they may be real. The transfer function may be for an unaugmented airplane, or one augmented with

back-up or "hard" SAS. Control system and higher order characteristics are included in $Y(s)_{cs}$. This may also be considered to be an equivalent system representation.

Parametric Criteria

The pilot rating data supporting the RSS criteria of Figure 1 are presented in Figure 8, and the correlation with the iso-rating lines is seen to be excellent. Each configuration evaluation consisted of three runs (A, B, and C), one in each level of turbulence, with the 150 ft ILS offset in Run B. Repeats were allowed when requested by the pilot. For each run, the pilots gave a separate rating for the ILS portion, visual short final, and visual flare and touchdown. The rating in Figure 8 is the worst of these three ratings.

Two levels of control sensitivity ($M_{\delta_{ES}}$) were used in the simulator experiement, the high ones for the data of Figure 8 (.43 and .34 rad/sec^2/in) and the low one (.085 or .086) for the data presented in Figure 9. There are fewer data points for the low sensitivity, and the dashed lines in Figure 9 involve heavy extrapolation. Though the faired curves in Figure 9 appear different from those in Figure 8, a closer look will show that they agree in the vicinity of $\lambda_{sp_1} = 0.1$, but the lower sensitivity data has a larger (worse) pilot rating, about 1-1/2 rating points, for coincident iso-rating lines. The major difference is a large degradation in pilot rating for $\lambda_{sp_2} = -2$ or -3 due to low sensitivity, reflected in the dashed lines. The low sensitivity data was used to help define the iso-rating lines and boundaries in Figure 1 around $\lambda_{sp_1} = 0$, also to decide on the cut-off at $\lambda_{sp_1} = .35$.

The data in Figure 8 define the effect of the two short-period roots (λ_{sp_1} and λ_{sp_2}) on pilot rating for a constant value of $Z_{\theta_2} \simeq -0.6$ rad/sec. The effect of Z_{θ_2} is shown in Figure 10 for two λ_{sp_1}, λ_{sp_2} combinations. The data are shown as increments in pilot rating (ΔPR) from the rating for the baseline case with $Z_{\theta_2} \simeq -0.6$. Configurations S23, S42, and S42A are the baseline ones, with S42A having the low sensitivity. Baseline pilot ratings may be read from Figures 8 and 9 (for specific values and details, refer to Appendix B, B.5.9.2). The degradation in pilot rating as Z_{θ_2} becomes more negative (i.e., slope of ΔPR with Z_{θ_2}) appears to be invariant of

Symbol	$M_{\delta_{ES}}$	Z_{θ_2}	Configs	Ratings
▽	.43	-.69	L71-73	Pilot A/R/T
⊙	.34	-.58	S21-24, S41-44, S60-63	Pilot A/R

PR = Worst, of ILS, Visual, FTD. Comma indicates repeat rating.

— — — Knee of curve from Figure B-21

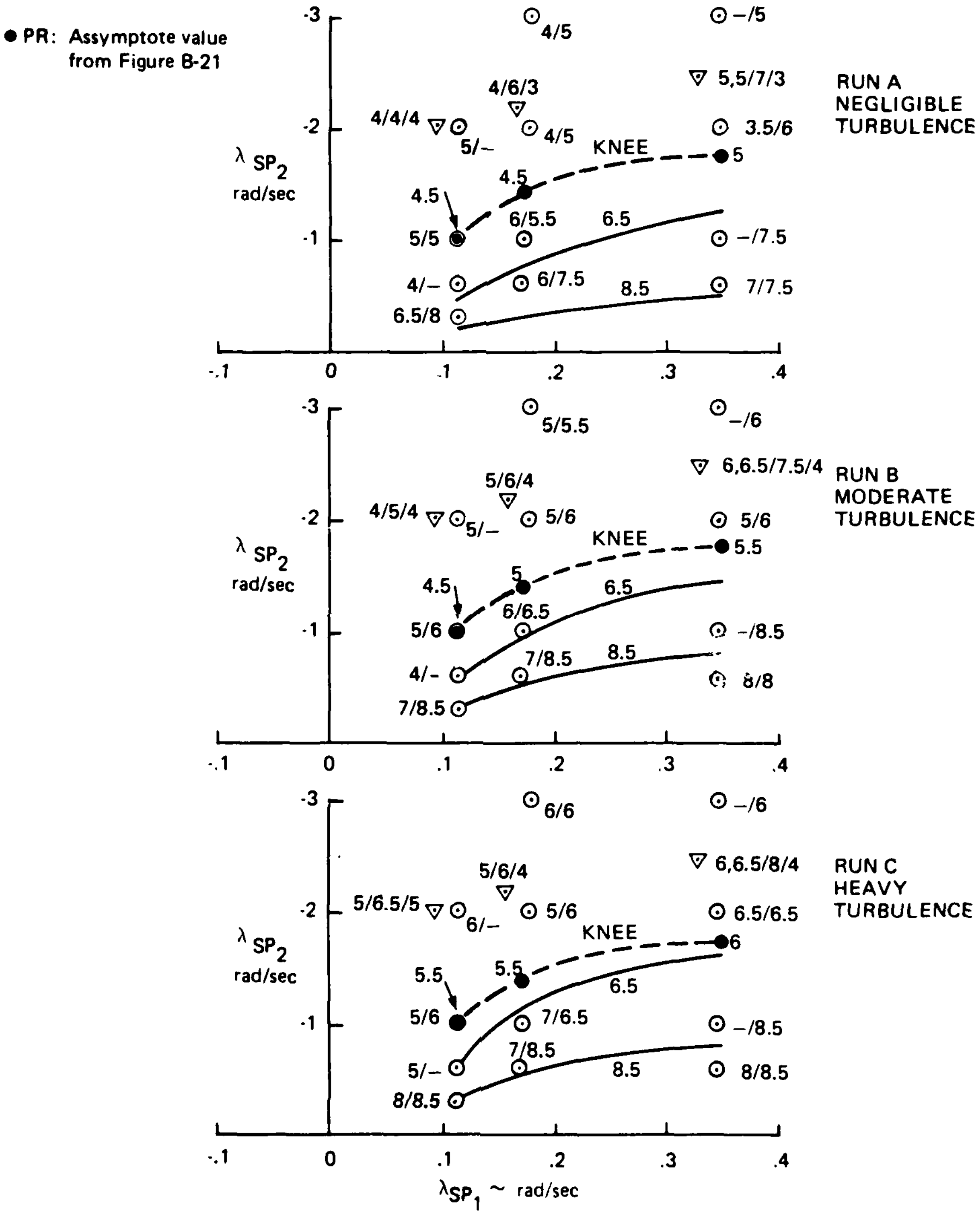


Figure 8 (3.2.1.3). Pilot Rating as Function of Real Roots (λ_{SP_1}, λ_{SP_2}) for High Sensitivities; $Z_{\theta_2} \cong -.6$

Symbol	$M_{\delta_{ES}}$	Z_{θ_2}	Configs	Ratings
◇	086	-.59	F1, F6, F4, F2	Pilot A/R/T
⊙	.085	-.58	S41A - 44A, S44B	Pilot A/R

Pilot ratings are average worst (of ILS, Visual, FTD) rating

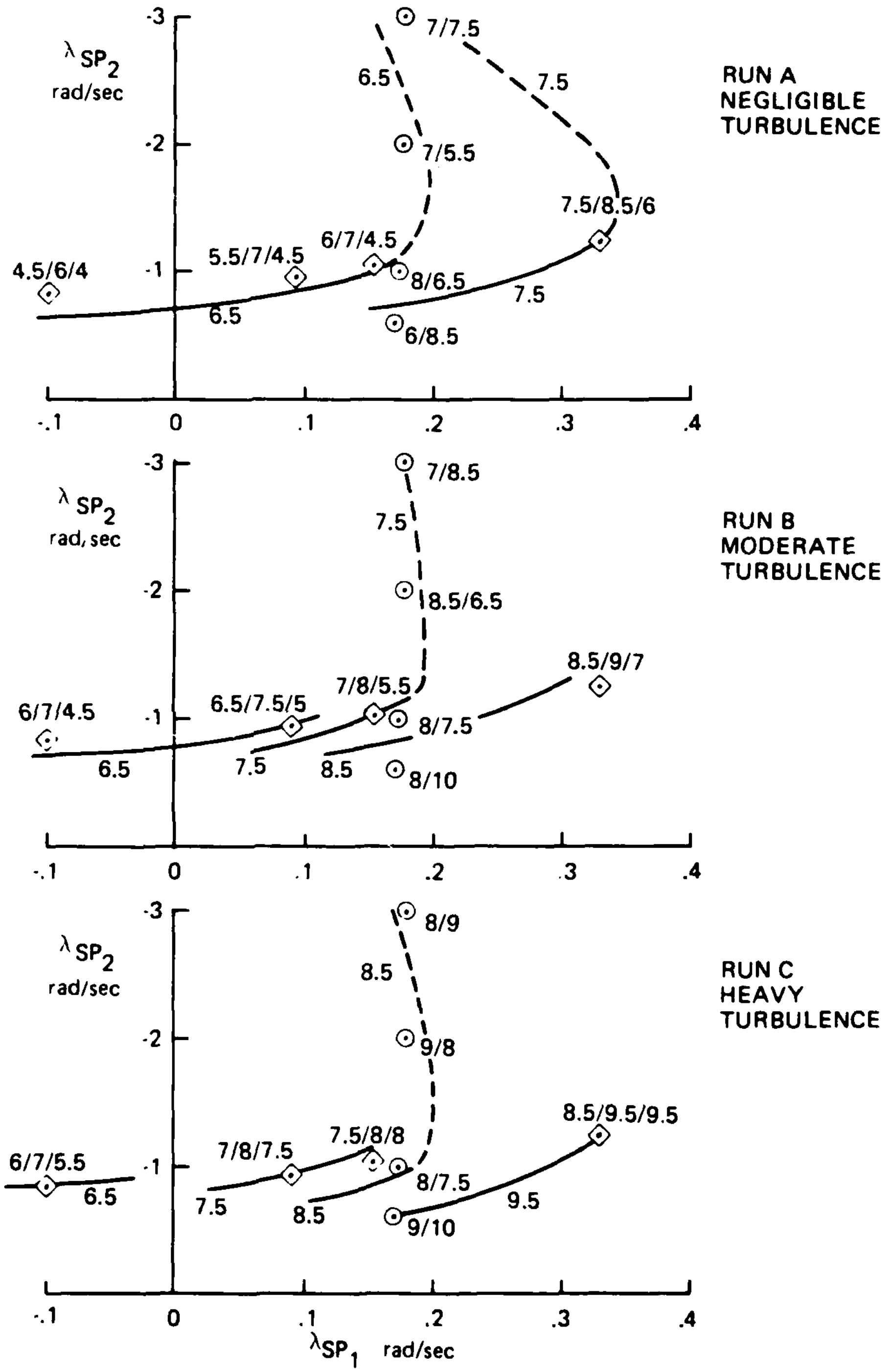


Figure 9 (3.2.1.3). Pilot Rating as Function of Real Roots (λ_{SP_1}, λ_{SP_2}) for Low Sensitivities; $Z_{\theta_2} \cong -.6$

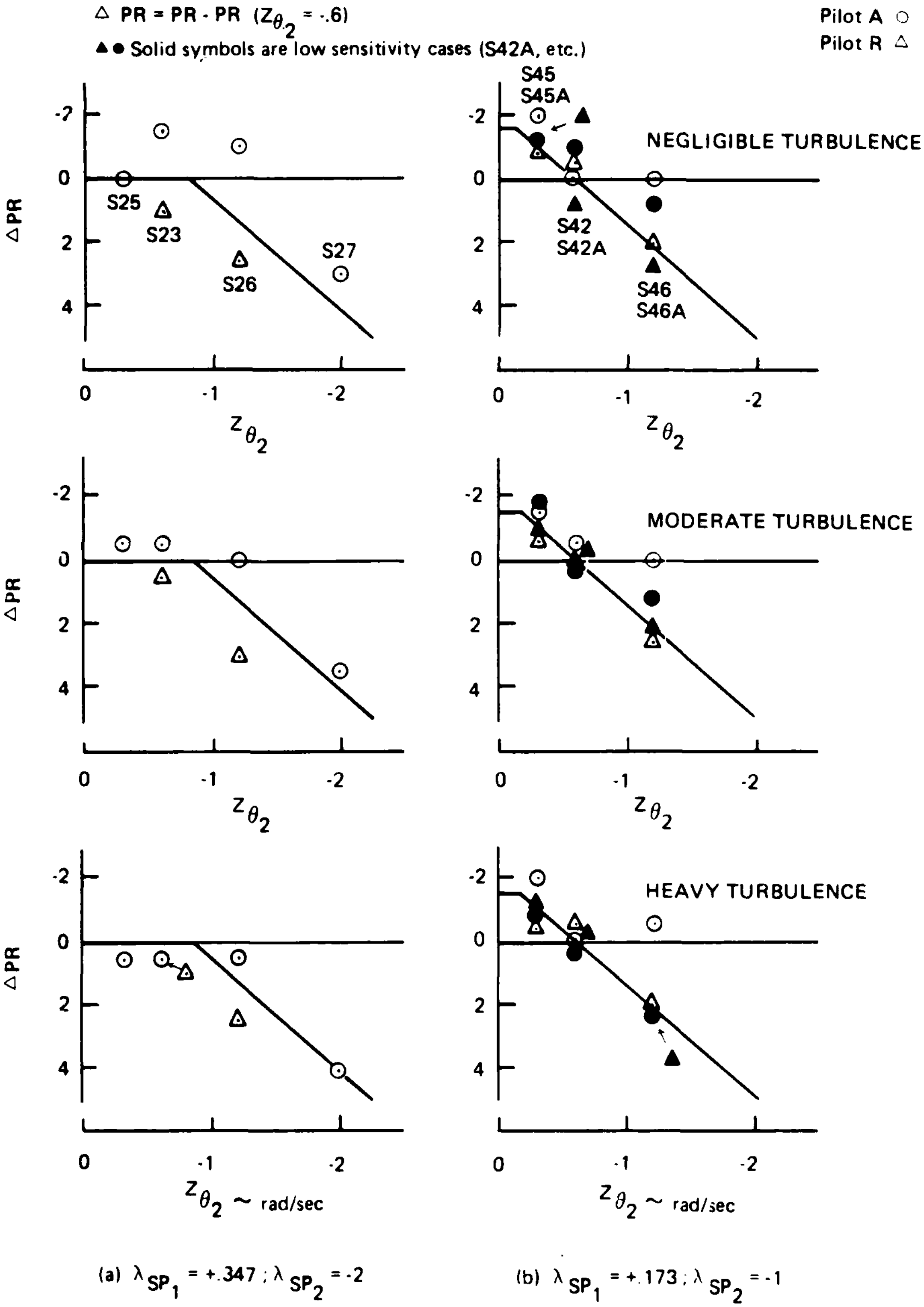


Figure 10 (3.2.1.3). Increment in Pilot Rating Due to Z_{θ_2} Zero

$$\Delta PR = PR\,(M_{\delta_{ES}} = .085) - PR\,(M_{\delta_{ES}} = .341)$$

Based on data of Figure 12

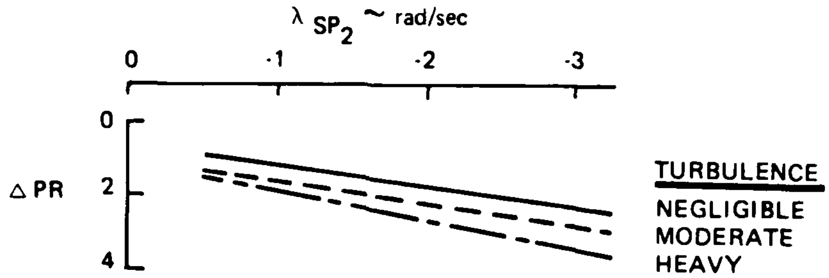


Figure 11 (3.2.1.3). Degradation in Pilot Rating Due to Low Control Sensitivity as Function of λ_{SP_2}

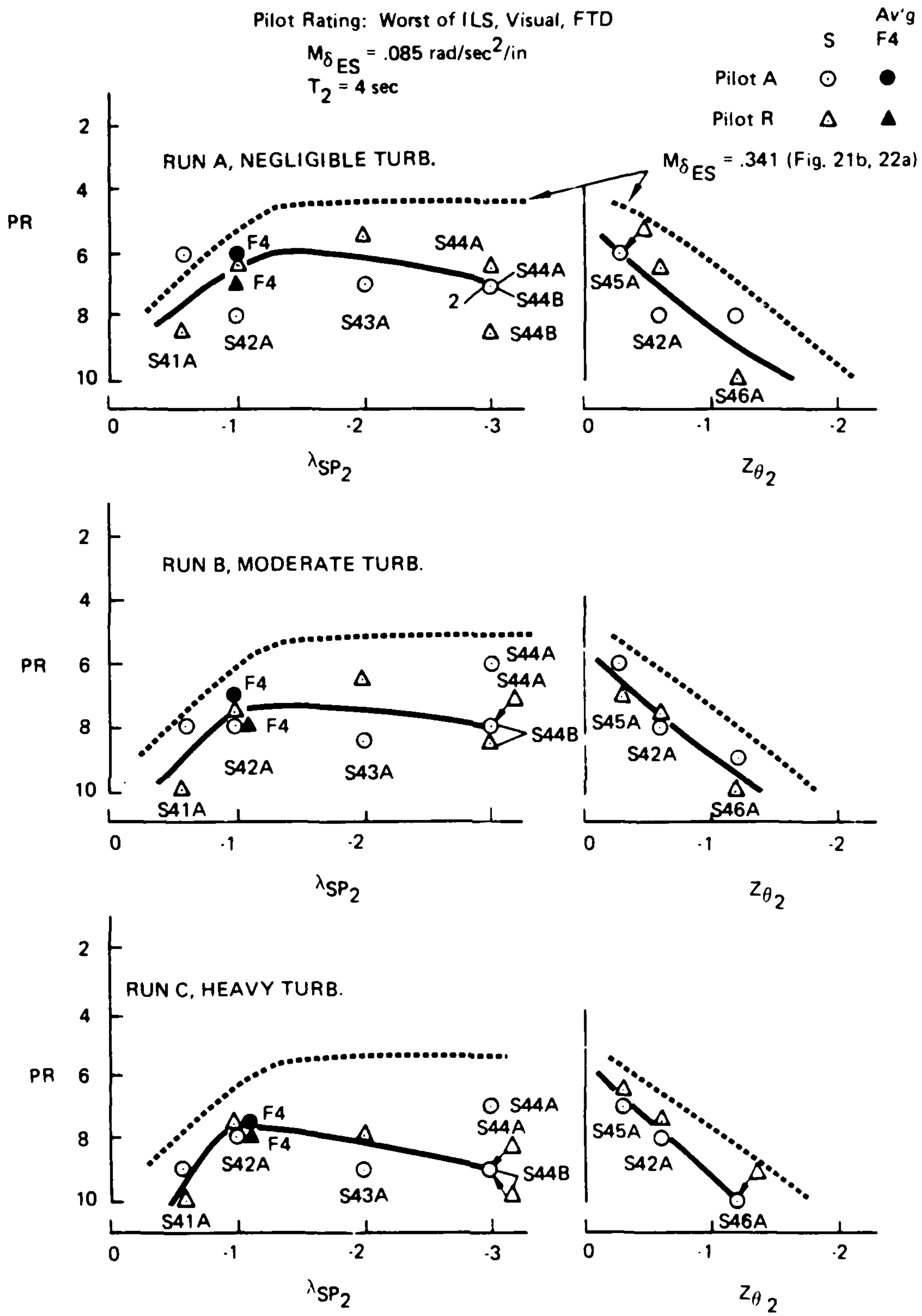


Figure 12 (3.2.1.3). Effect of Control Sensitivity ($M_{\delta_{ES}}$) on Pilot Rating

λ_{sp_1}, λ_{sp_2}, $M_{\delta_{ES}}$, or turbulence intensity. However, the minimum (best) pilot rating, with decreasing magnitude of Z_{θ_2}, corresponds to the critical value (Figure 1) or the "KNEE" value (Figure 8). This is the basis for the cut-off or upper limit of ΔPR shown by the faired lines in Figure 10. The criteria for correcting for $Z_{\theta_2} \neq -0.6$ in Figure 2 come directly from the faired lines in Figure 10.

The basis for the correction for low control sensitivity (Figure 3 of the criteria) is found in Figure 11, and is simply the average of the three curves in Figure 11. The data in Figure 11 is in turn based on the data in Figure 12. Shown in Figure 12 are pilot ratings plotted vs λ_{sp_2} (left side) and vs Z_{θ_2} (right side), all for λ_{sp_1} = .173 (or T_2 = 4 sec) and $M_{\delta_{ES}}$ = .085 rad/sec²/in. The dashed curves are fairings of the data for $M_{\delta_{ES}}$ = .341 rad/sec²/in, plotted in similar form. The comparison presented in Figure 12 shows the increasing degradation (ΔPR) in pilot rating as λ_{sp_2} becomes more negative, also the increased degradation with turbulence for large λ_{sp_2}. It also shows no change in ΔPR with Z_{θ_2}. For each S configuration with low sensitivity plotted in Figure 12 (A indicates low $M_{\delta_{ES}}$), there was a corresponding S configuration with high sensitivity. The increment between these two sets (low and high $M_{\delta_{ES}}$) was plotted, and the data faired to produce Figure 11. Though not shown, the increments (ΔPR) were very close to the lines in Figure 11. Since the correction for $M_{\delta_{ES}}$ was only for a discrete decrement, and rather crude for want of data, to include more than a single average curve in Figure 3 is not justified.

The analysis of the pilot rating data in Appendix B includes numerous plots illustrating the effect of the various experiment parameters. Two of these, cross plots of the data in Figure 8, are presented as Figures 13 and 14, and are particularly helpful in understanding the effects of λ_{sp_1} and λ_{sp_2} on flying qualities.

Figure 13 shows, for large λ_{sp_2}, the variation of pilot rating with λ_{sp_1} or T_2. There isn't any! This result is at total variance with generally held concepts that pilot rating is a function of T_2 (e.g., MIL-F-8785C gives 6 sec as the limit for Level 3). It may be noted that all ratings in Figure 13 are 6.5 or better, even for T_2 = 2 sec. in heavy turbulence. Also note that Pilot A's evaluation of S23 (T_2 = 2 sec) in smooth air was PR = 3.5. Since Pilot A refused to rate

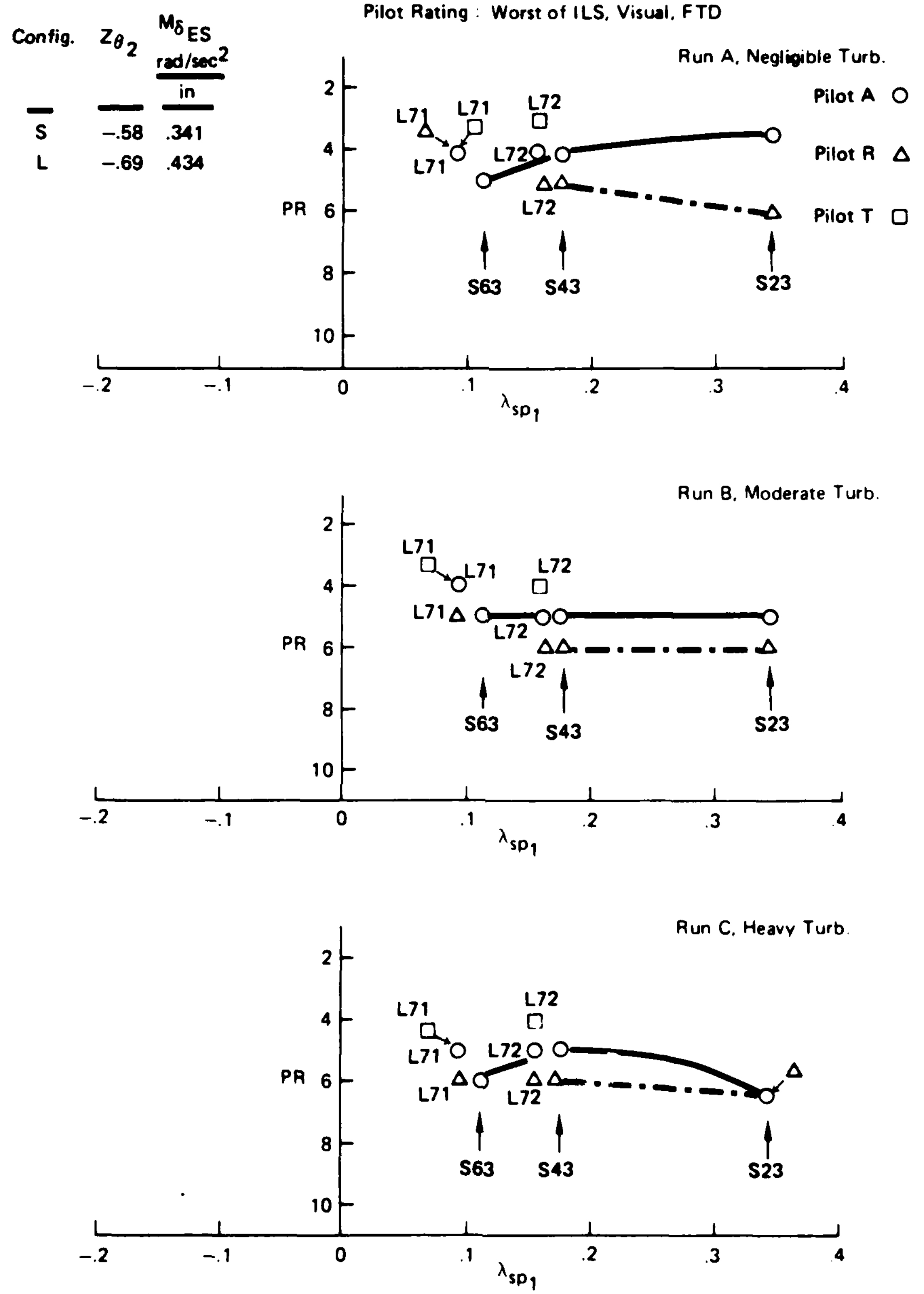


Figure 13 (3.2.1.3). Pilot Rating vs Unstable Root (λ_{sp_1}) for λ_{sp_2} = −2.0

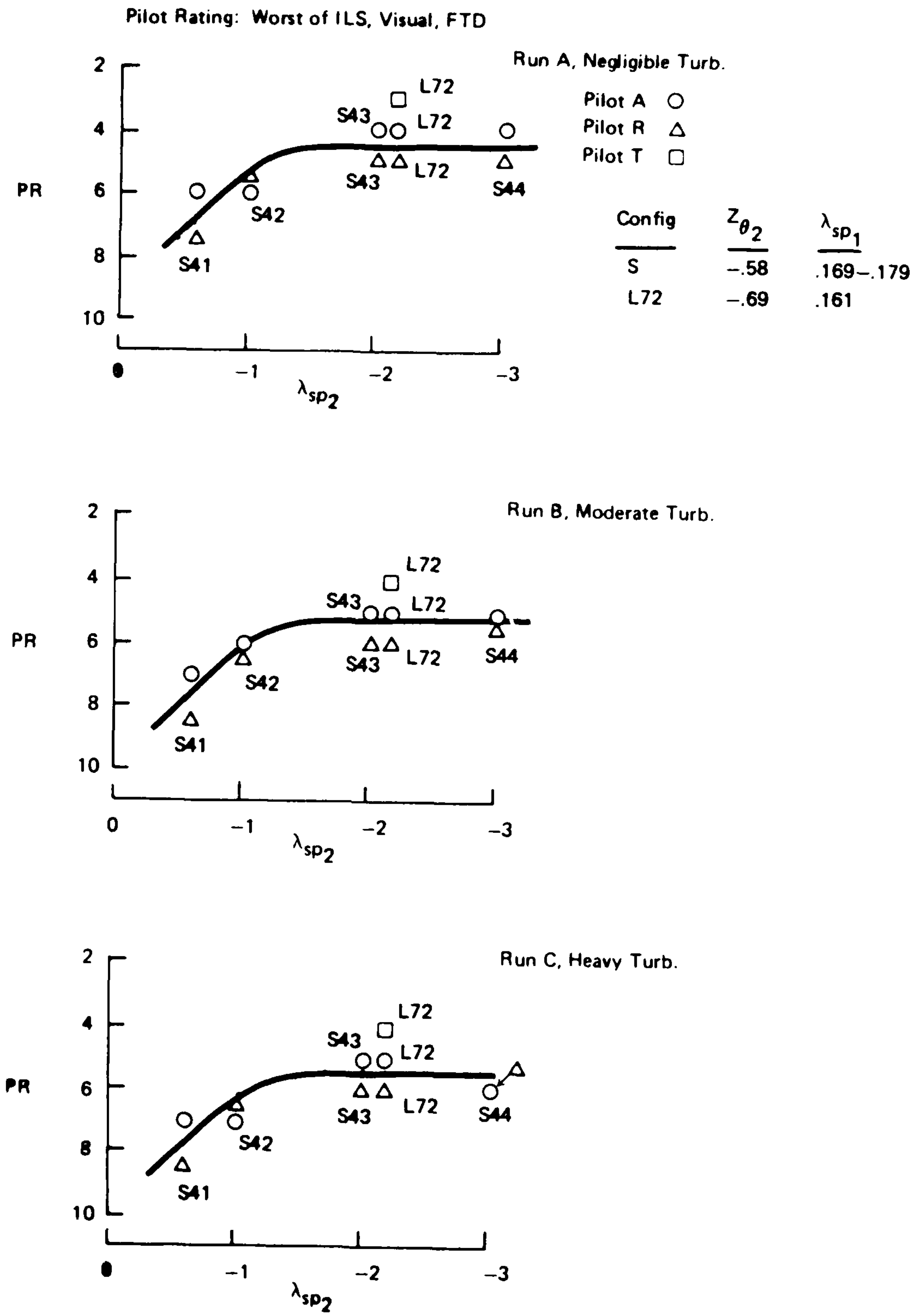


Figure 14 (3.2.1.3). Pilot Rating vs Stable Short-Period Root (λ_{sp_2}) for T_2 = 4 sec (λ_{sp_1} = .173)

an unstable configuration better than a 4, he apparently didn't even know S23 was unstable in smooth air. Non-recognition of significant instability was also noted by Smith (Ref. 8) for the RSS configurations in the LAHOS flight tests. Referring to Figure 1, it can be seen that for λ_{sp_2} above critical, the variation of PR with T_2 is small, but for λ_{sp_2} below critical, the variation can be large. Also, in most studies (usually ground simulator) where PR is defined as a function of T_2, the variation of T_2 is produced by moving the c.g. When c.g. position changes, other parameters change as well as T_2 or λ_{sp_1} (e.g., F configuration variations in Appendix B).

Figure 14 shows the effect of varying λ_{sp_2} on pilot rating for T_2 = 4 sec. Note the rapid improvement (decrease in PR) as the magnitude of λ_{sp_2} becomes more negative for small negative values of this parameter, the "knee" at $\lambda_{sp_2} \approx -1.5$, and the constant PR for larger negative λ_{sp_2}. The "knee", plotted in figure 8, is the "critical" value of Figure 1. From either figure, it may be seen that the critical value of λ_{sp_2} increases negatively with increasing λ_{sp_1} (or as T_2 gets smaller). Below this critical value, pilot rating drops off (degrades) rapidly with λ_{sp_2} (decreasing magnitude).

Frequency Response Criteria

The closed-loop analysis method of the RSS criteria was applied to all configurations in the approach and landing simulator experiment. The resonant amplitude (RA) and compensation or pilot lead (ϕ_{PL}) are plotted, with configuration identifiers for each, on Figure 15 for BW = 1 and 3 rad/sec. The θ/F_s transfer function used included feel system, actuator, and phugoid dynamics. The F cases are the F-111A with various c.g.'s; the L cases are the LAHOS simulations; the S cases are simulation configurations with independent parametric variations of λ_{sp_1}, λ_{sp_2}, and Z_{θ_2}.

It is useful to look at the variations on Figure 15, starting with BW = 1 rad/sec (upper half). The solid lines through S cases are for λ_{sp_2} variations, and are horizontal and concave up showing primarily an effect on ϕ_{PL}. The dashed lines through S cases are for Z_{θ_2} variations, and are horizontal but concave down, again showing primarily

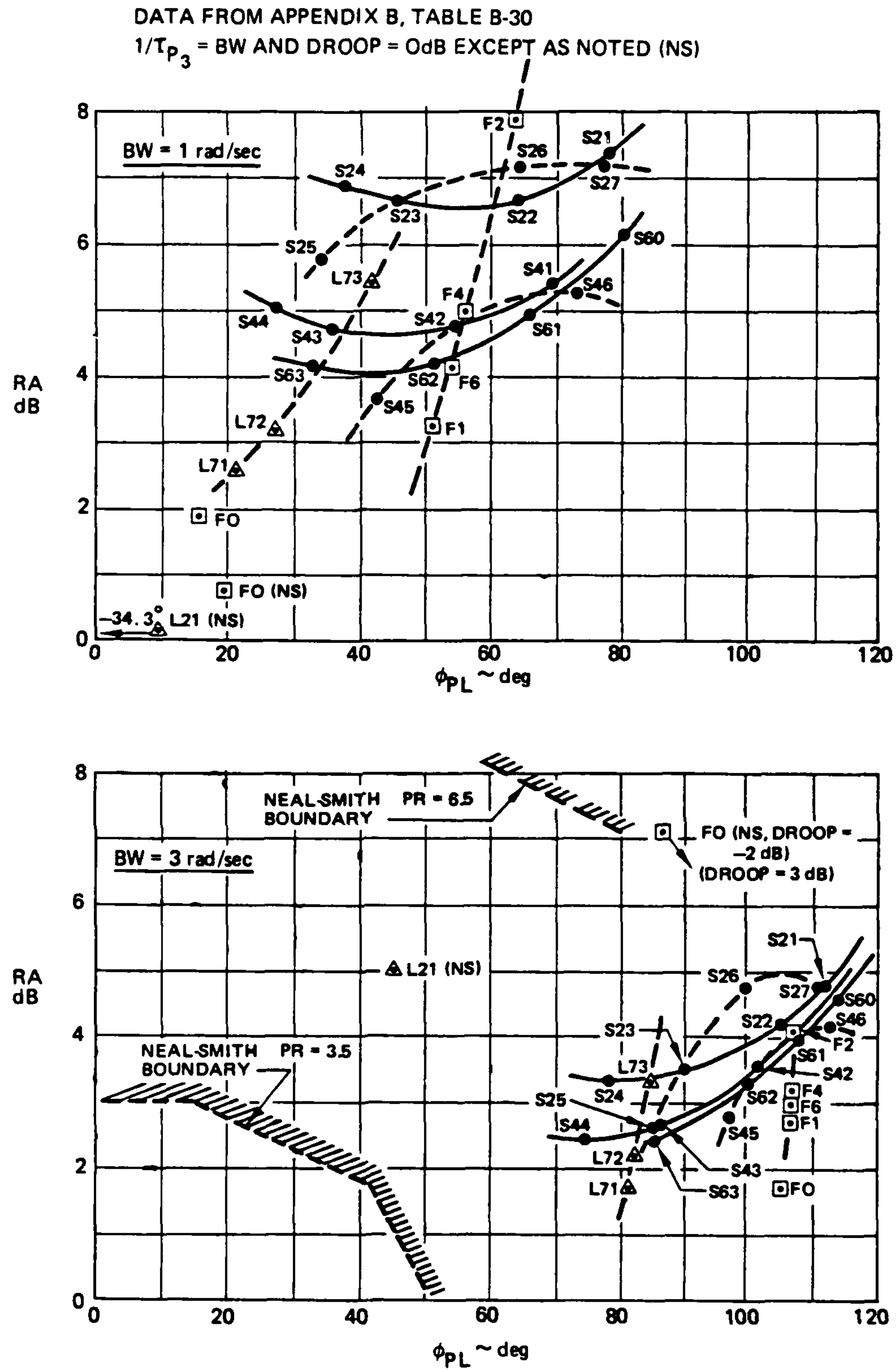


Figure 15 (3.2.1.3). Resonant Amplitude and Pilot Lead for All Simulator Configurations

a ϕ_{PL} effect. The different S case lines, solid and dashed, have varying λ_{sp_1} (e.g., S63 has T_2 = 6 sec, S23 has T_2 = 2 sec, but both have the same λ_{sp_2} and Z_{θ_2}). Thus the effect of λ_{sp_1} is primarily on RA. The F cases, with varying c.g., have a primary effect on RA with even less variation of ϕ_{PL} than for the λ_{sp_1} variations of the S cases. The L cases, with varying C_{m_α} produced by varying the α/δ_e feedback gain, have effects similar to those of λ_{sp_1}. Configuration L21, with Level 1 values of ω_{nsp} and ζ_{sp}, had RA and ϕ_{PL} calculated using standard Neal-Smith conditions. F0, on the lower ω_n boundary between Level 1 and Level 2 of the MIL-F-8785C short-period requirements, had RA and ϕ_{PL} calculated using both standard Neal-Smith and RSS criteria conditions. Lead (ϕ_{PL}) is not much different between the two, resonance is larger using RSS conditions, but both are within the Neal-Smith Level 1 boundary (see lower half of Figure 15).

For BW = 3 rad/sec (lower half, Fig. 15), the most important fact is the small area of RA vs ϕ_{PL} covered by all the RSS cases, and the narrow band these small variations fall in (F0 to F4 excepted). For comparison, the standard Neal-Smith Level 1 (PR = 3.5) and Level 2 (PR = 6.5) boundaries are also shown. These boundaries are also meant to apply for BW = 1 rad/sec.

The pilot rating data for the high sensitivity configurations are presented in Figure 16 (parts (a) and (b)) for BW = 1 rad/sec. The ratings are mostly those of pilots A and R, but L configurations were also rated by pilot T. Pilot T tended to rate better (lower PR) than the other two, except for the worst cases. Pilot R tended to rate one point lower than Pilot A. A few ratings have a - above or a + below them, indicating that analysis of the pilot comment data and test engineers observations strongly suggest that the rating should have been smaller (-) or larger (+). The ratings given are the worst of the three individual ratings the pilot assigned for the ILS portion, visual short final, or flare and touchdown.

Iso-rating lines have been drawn on Figure 16, different for each of the three turbulence intensities. Careful examination will show that the correlation with the iso-rating lines is excellent if the three (or two) pilot's ratings are taken in aggregate. There are no anomalous ratings

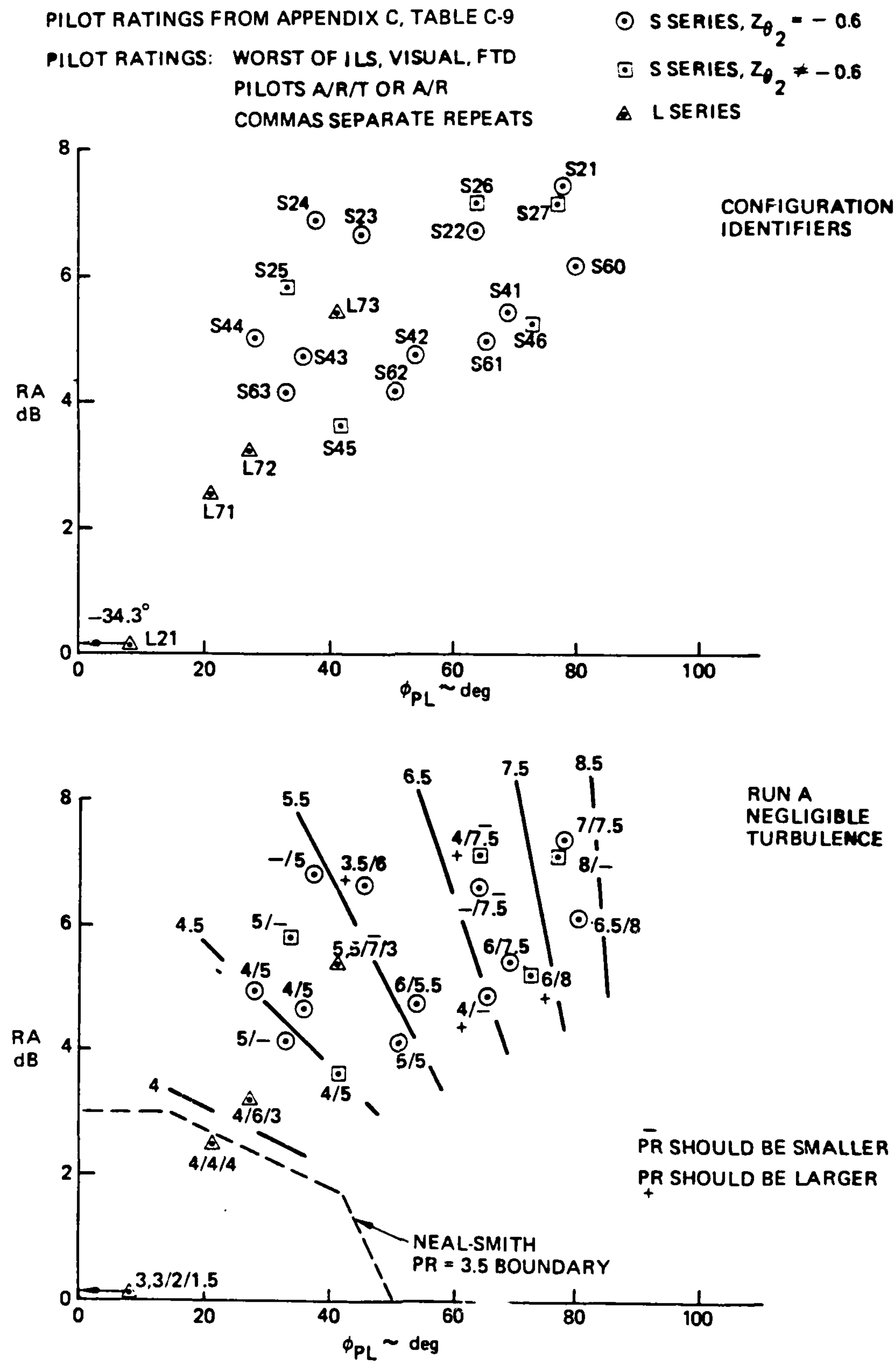


Figure 16 (3.2.1.3). Pilot Rating vs RA and $\emptyset_{PL}$, High Sensitivity, BW =1 rad/sec (a) Configuration Identifiers and Run A

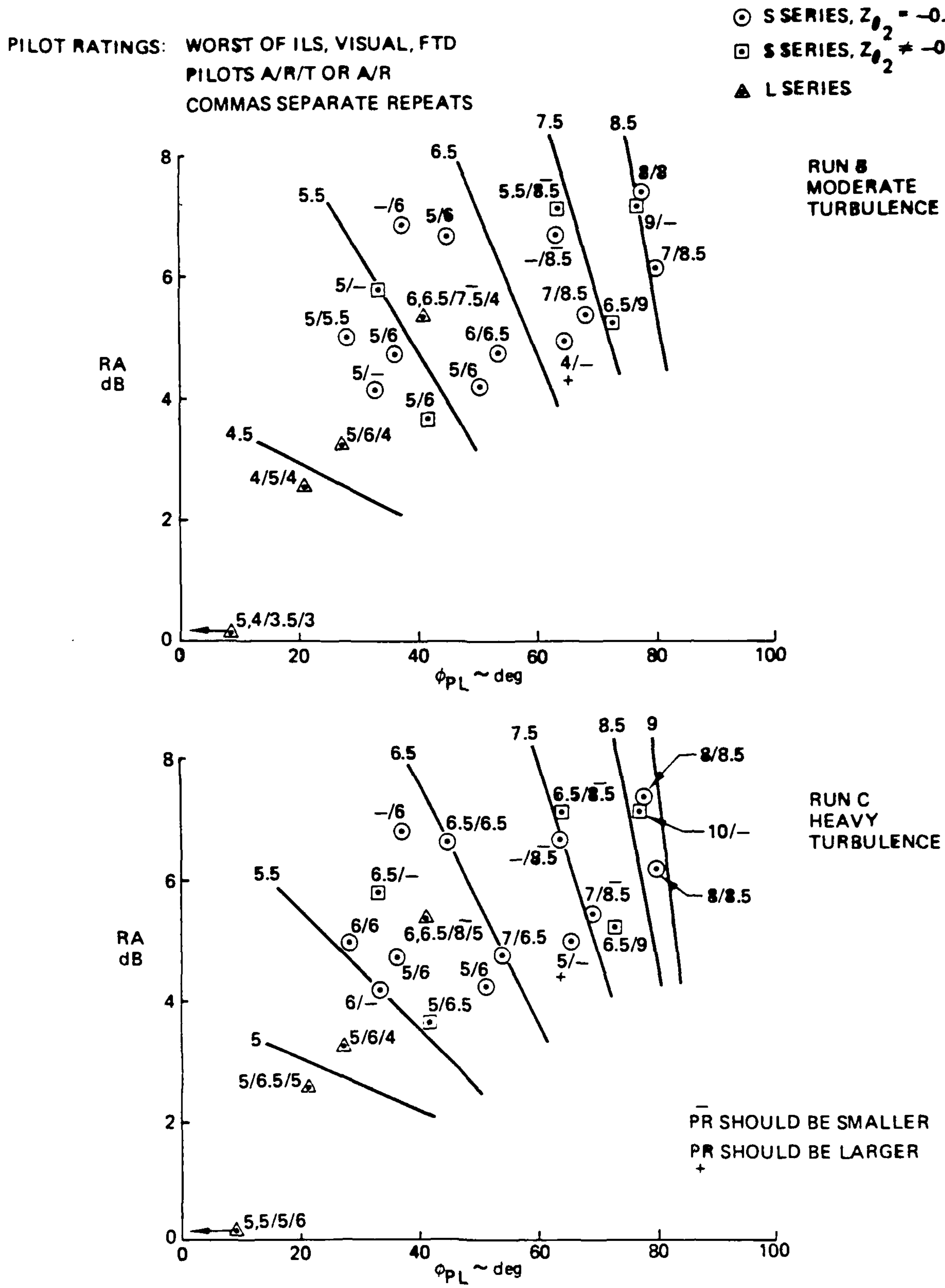


Figure 16 (3.2.1.3). Pilot Rating vs RA and ϕ_{PL}, High Sensitivity, BW = 1 rad/sec
(b) Run B and Run C

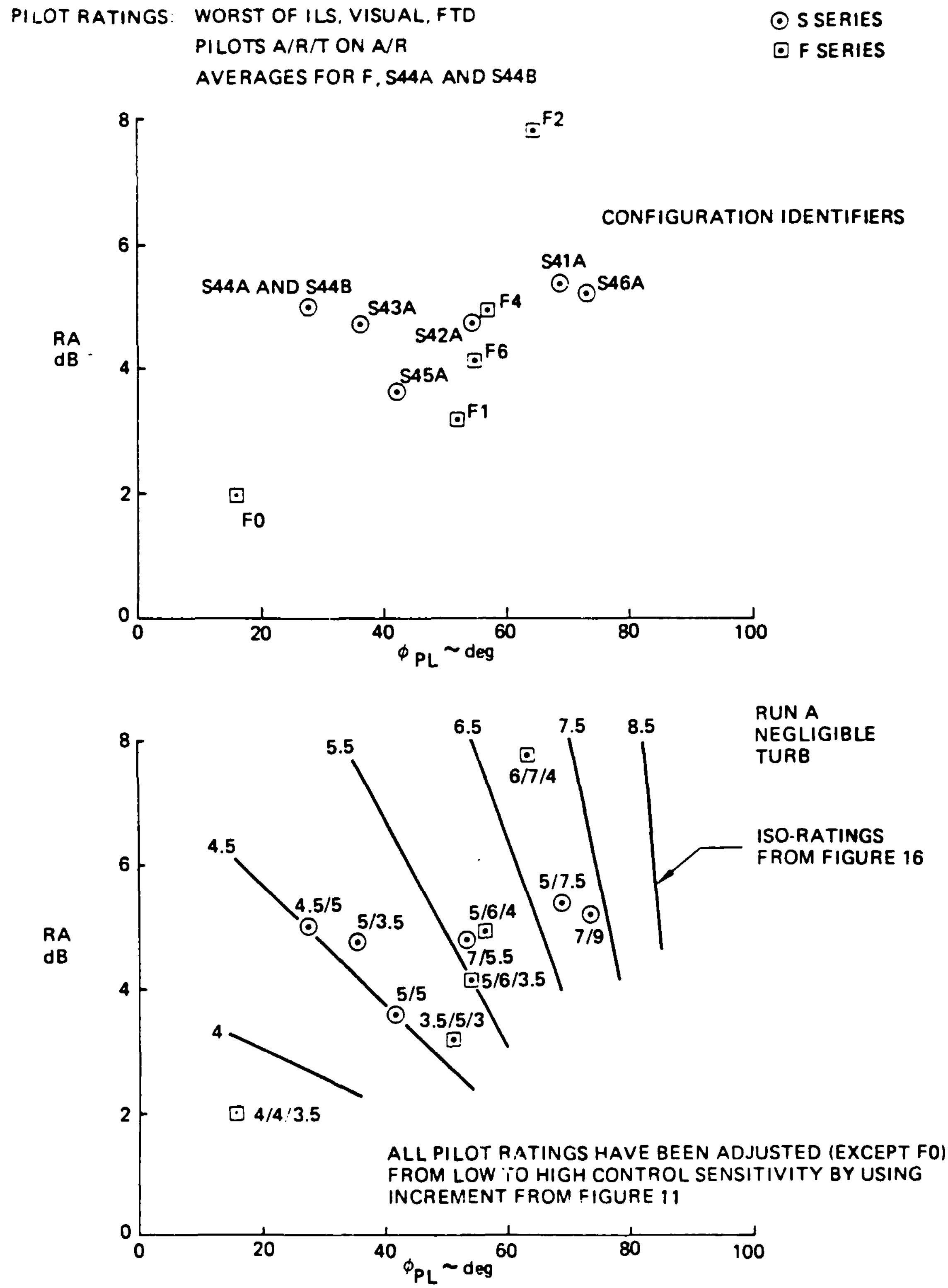


Figure 17 (3.2.1.3). PR vs RA and ϕ_{PL}, Adjusted Low Sensitivity, BW = 1 rad/sec
(a) Configuration Identifiers and Run A

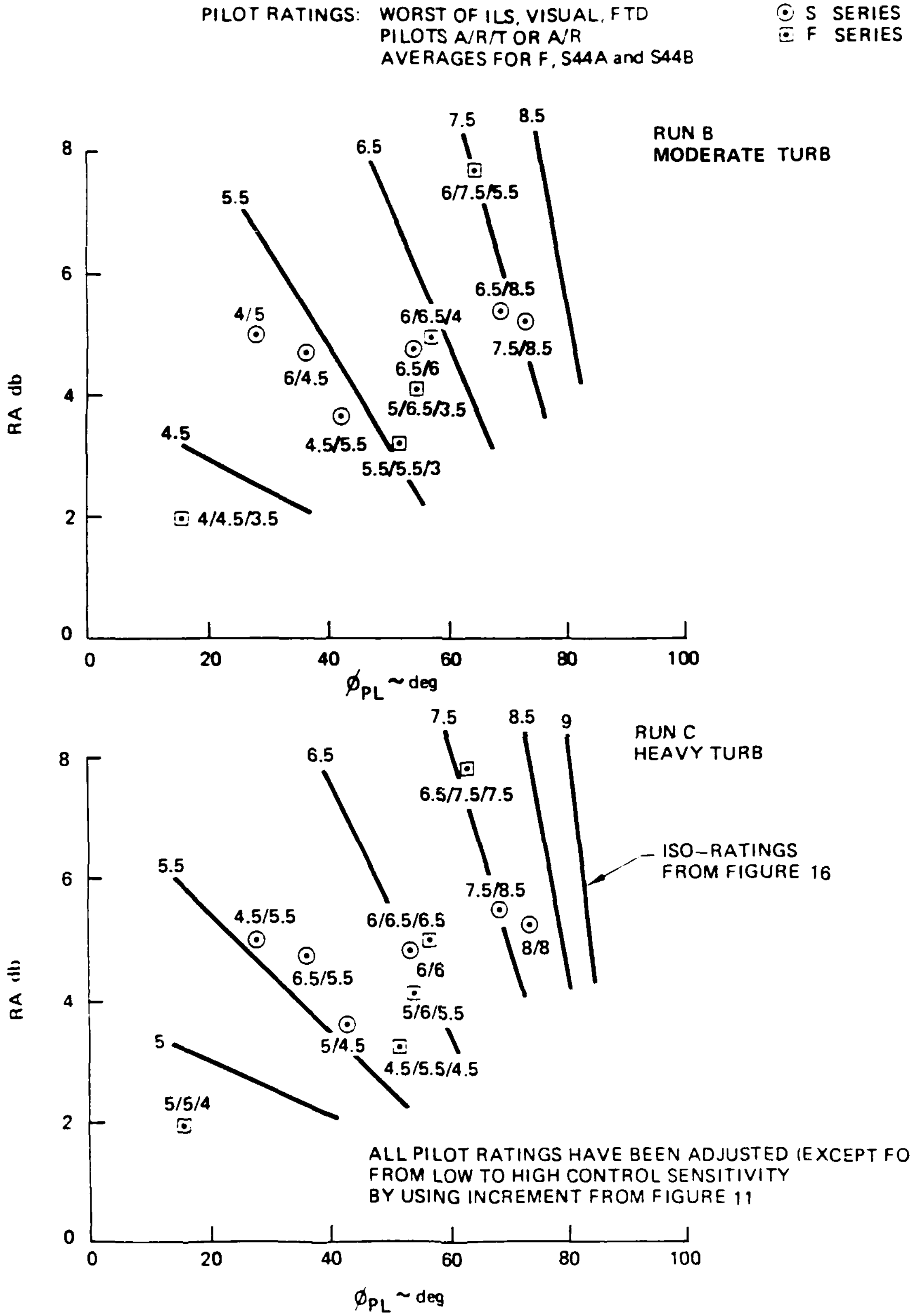
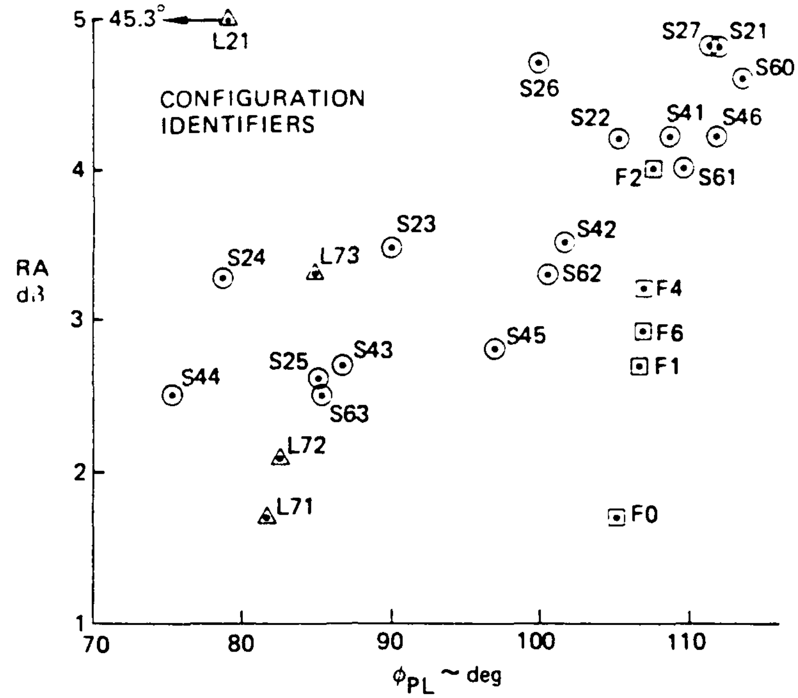


Figure 17 (3.2.1.3). PR vs RA and ϕ_{PL}, Adjusted Low Sensitivity, BW = 1 rad/sec
(b) Run B and Run C

ALL PILOT RATINGS ARE AVERAGES ACROSS PILOTS (TABLE B-31). ( ) INDICATE RATINGS ADJUSTED FOR LOW SENSITIVITY.

S SERIES
L SERIES
F SERIES



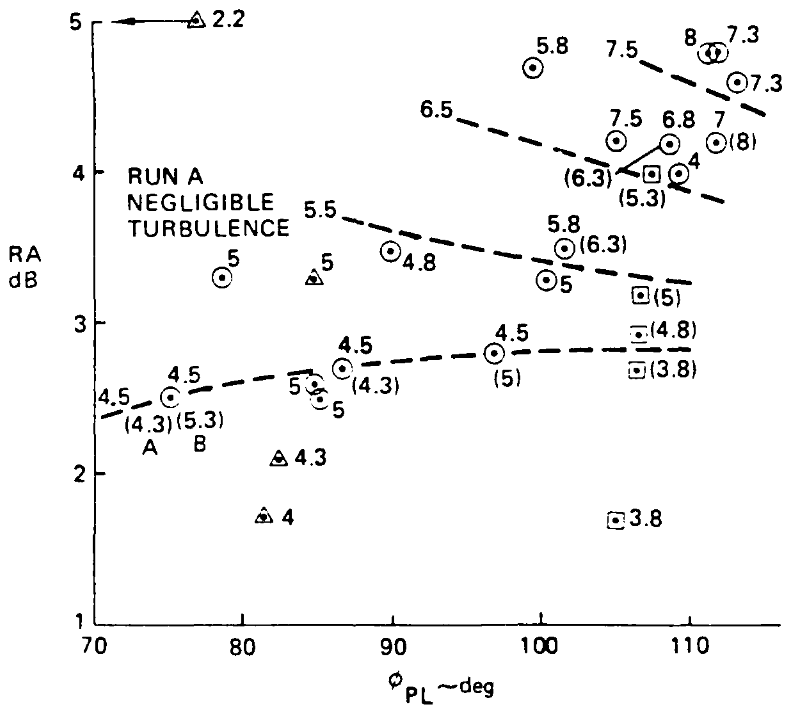


Figure 18 (3.2.1.3). Pilot Rating vs Resonant Amplitude and Pilot Lead, BW = 3 rad/sec
(a) Configuration Identifiers and Run A

ALL PILOT RATINGS ARE AVERAGES ACROSS PILOTS (TABLE B-31). ( ) INDICATE RATINGS ADJUSTED FOR LOW SENSITIVITY.

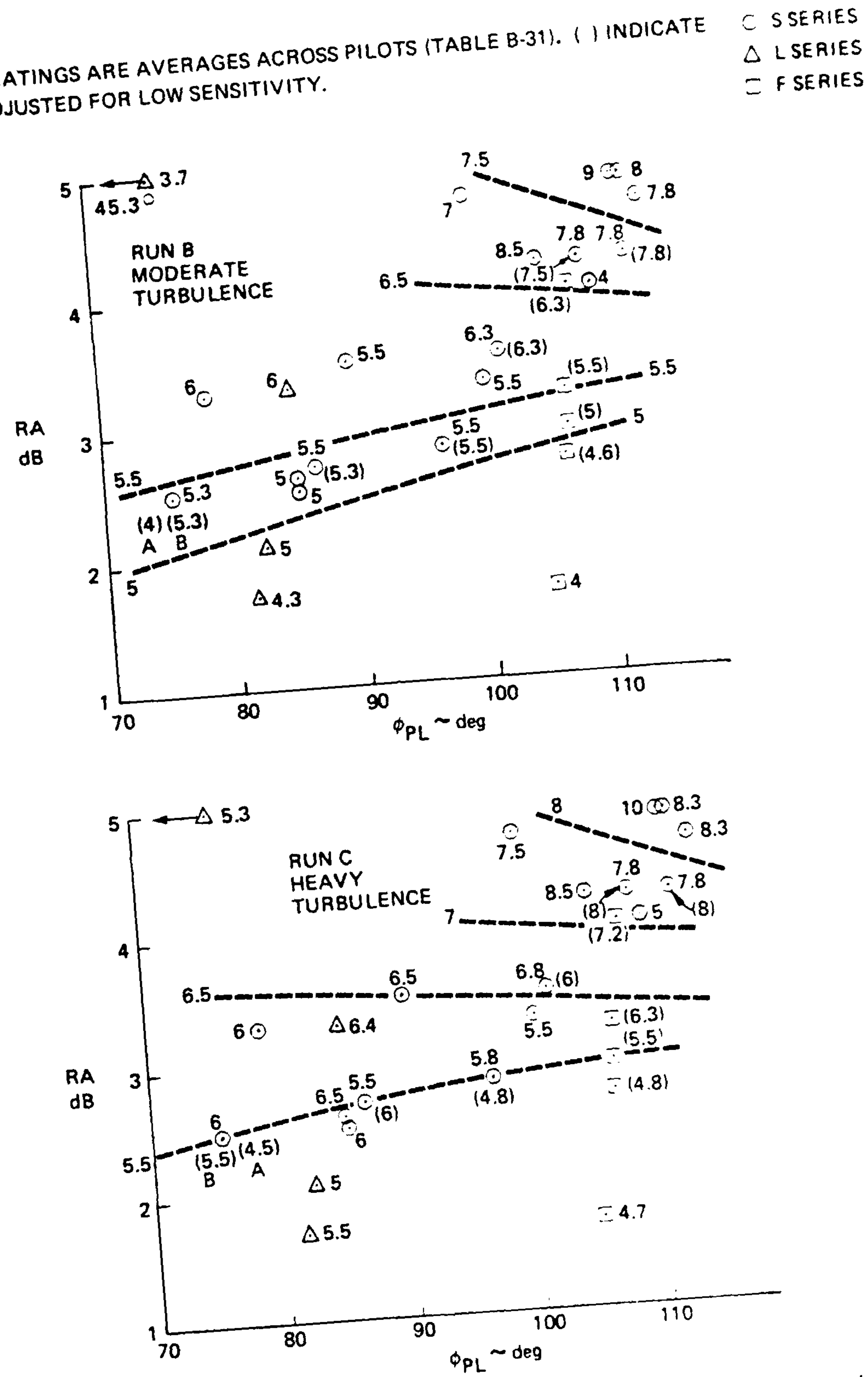


Figure 18 (3.2.1.3). Pilot Rating vs Resonant Amplitude and Pilot Lead, BW = 3 rad/sec
(b) Run B and Run C

except those for which a + or - indicates an appropriate warranted rating change. The Neal-Smith Level 1 (PR = 3.5) boundary is shown for the negligible turbulence case (Figure 16(a), lower half), and somewhat surprisingly, it seems to correlate well with the other iso-rating lines, particularly in slope.

It is important to recognize that the remarkably good correlation shown in Figure 16 covers not only variations in the short-period roots (λ_{sp_1}, λ_{sp_2}) but also variations in the large numerator (Z_{θ_2}) of the θ/δ_e transfer function.

Since the closed-loop analysis methods (RSS or Neal-Smith) cannot account for the effects of control sensitivity on flying qualities, the pilot rating data for the low sensitivities ($M_{\delta_{ES}}$ = .085) can not be compared directly with the high sensitivity data ($M_{\delta_{ES}}$ = .34, .43). However, if the correction for low sensitivity from Figure 11 is applied, then how this data correlates with RA and ϕ_{PL} becomes a test of both the correction and the closed-loop iso-ratings of Figure 16. The test is significant only for the F configurations, since pilot ratings for these were not used in deriving the correction for low $M_{\delta_{ES}}$. The correction of Figure 11 was applied to the pilot ratings for all configurations with low sensitivity and the data plotted in the RA vs ϕ_{PL} plane (Figure 17) with the iso-rating lines from Figure 16. Pilot ratings for the F configurations correlate well with the iso-rating lines, provided it is accepted that pilot T tends to rate the better configurations too good (too low a PR).

For BW = 3 rad/sec, configuration identifiers and pilot ratings for the three turbulence levels and including ratings corrected for low $M_{\delta_{ES}}$ are plotted on the RA vs ϕ_{PL} plane in Figure 18. The scales are much larger than those of Figure 15 to provide space for the rating data. The ratings are averaged across the pilots. The iso-rating lines, fairly well defined in the neighborhood of RA = 3, are primarily horizontal rather than vertical as for BW = 1 rad/sec.

The iso-ratings lines from Figure 16 and Figure 18 were used to construct the Level 2 and 3 boundaries in Figure 4. The Neal-Smith Level 2 boundary was used as a cut-off for the BW = 1 rad/sec Level 2 boundaries at high resonant amplitude. Substantial extrapolation was used in defining the Level 3 boundary: all levels of turbulence were combined as

they were close together; the slope was set equal to the slope of the Neal-Smith Level 2 boundary.

Other Flight Phases

There is not much in the way of supporting data for extending the approach and landing data to other flight phases. However, the requirements in MIL-F-8785C for short-period frequency and damping for normal aircraft show Category A requirements very similar to Category C requirements - the boundaries on minimum frequency are somewhat higher for Category A, the rest are the same except for Class related differences at very low n/α. On this basis, the application of the approach and landing requirements for relaxed static stability, both parametric and frequency response, to Category A appears warranted. There is a new appreciation that the flare and touchdown part of landing is a task demanding the same precision in attitude control as Category A flight phases (e.g., Ref. 8). Thus any Category C flight phase, such as LAPES (low altitude parachute extraction), which requires precise flight close to the ground would require flying qualities like those of landing (flare and touchdown).

The only known data on Category B requirements for relaxed static stability are given by Bull (Ref. 28) in connection with a B-26 landing approach program, and are only qualitative. The relative difficulty of the landing task and instrument enroute flying was investigated briefly. "The evaluation pilot, under the hood, flew the airplane and performed the usual cockpit duties of handling the radio navigation equipment and keeping track of his progress. The tests were all conducted in smooth air -- configurations were near the boundary of unflyability -- results indicated mirror landing was the more demanding task." Bull gives no indication of the amount of time the pilot spent flying the enroute task. The ten minute limit specified in the recommendation for Level 3 is probably conservative, but it should allow adequate time for reversion to a more benign condition with Level 2 flying qualities.

Certain Category C flight phases do not demand precision attitude control, notably takeoff and waveoff. Waveoffs were performed in the ground simulator experiment of this report (App. B), and were found less demanding (a PR = 10 in flare and touchdown became a PR = 7 in waveoff).

Accordingly, requirements for these less demanding tasks are classed with Category B tasks.

The accident/incident data in Appendix A show that additional flight duties and responsibility for configuration control are a significant contributor to accidents in approach and landing (Fig. A-6). Based on this knowledge, and the fact that attitude stabilization of an unstable configuration requires continuous attention from the pilot (demonstrated by the pilot comments in Appendix G), it is recommended that the contractor be responsible for ensuring that the additional duties required of the pilot are compatible with the attention he must devote to attitude stabilization.

Long Period Oscillation and Flight Path Stability

The simulator data (App. B) upon which the short period and frequency response requirements are based had the following envelope of long period oscillation characteristics.

$.02 < \omega_{n_p} < .3$ (rad/sec)

$.01 < \zeta_p < .8$

$-0.8 > Z_{\theta_1} = -1/T_{\theta_1} > -.14$ (rad/sec)

$-.003 > d\gamma/dV > -.149$ (deg/knot)

Nominal approach speeds were 120 and 145 knots.

The stated requirements are based on extrapolation of existing data, primarily in the MIL-F-8785B BIUG (Ref. 2), using the above envelope for guidance.

3.2.3 Residual Pitch Oscillations - Revision

A. REASON FOR THIS REQUIREMENT

The primary purpose of the requirement is to prevent limit cycles in the control system or structural oscillations which might compromise tactical effectiveness, cause pilot discomfort, etc.

B. RELATED MIL-F-8785C REQUIREMENT

3.2.2.1.3

C. STATEMENT OF THE REQUIREMENT

3.2.3 Residual Pitch Oscillations. Any sustained residual oscillation shall not interfere with the pilot's ability to perform the tasks required in service use of the airplane. Any sustained residual oscillation, controls fixed or controls free, in calm air, shall not exceed ______________.

D. RECOMMENDATION

Any sustained residual oscillation, controls fixed or controls free, in calm air, shall not exceed in amplitude the following values.

Any flight phase:

Level 1 normal acceleration	±values in Figure 1
Level 2 normal acceleration	±0.05g

Any Category A and C flight phases requiring precise attitude control:

Level 1 pitch attitude	±0.05 degrees
Level 2 pitch attitude	±0.2 degrees

E. RATIONALE BEHIND REQUIREMENT

Data generated by the B-52 CCV program (Ref. 21) indicates that the amplitudes for residual oscillation as specified in 3.2.2.1.3, MIL-F-8785C, are too large and need to be reduced. It is felt that, for Level 1, these amplitudes should not be perceptible to the pilot, but for Level 2 some relaxation should be allowed. Accordingly, amplitudes for normal acceleration versus frequency that represent 80% of the mean perceptible from Reference 22 are recommended for the Level 1 requirements. A similar reduction (from MIL-F-8785C) is also recommended for the Level 1 requirements for pitch attitude in those Category A and C flight phases where precise control of attitude is required. For the Level 2 requirements, the values in MIL-F-8785C have been retained.

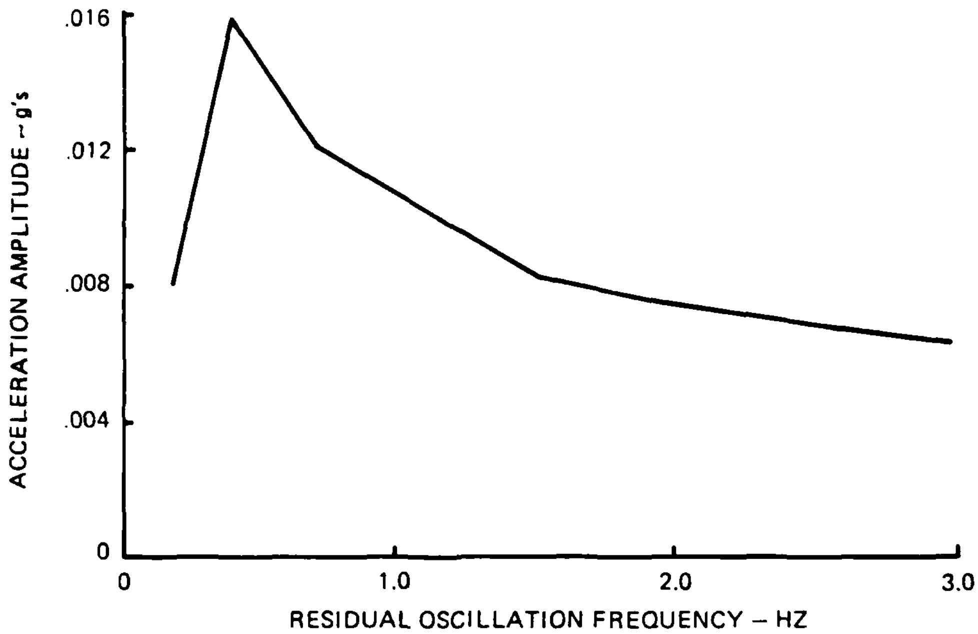


Figure 1 (3.2.3). Vertical Sustained Residual Oscillation Limitation

However, the ±3 mil (±0.172 degrees) requirement on attitude has been converted to degree units, and increased slightly in the rounding off process.

The requirement on pitch attitude for Category A flight phases has been broadened to Category A and C flight phases in view of recent recognition that landing is a task requiring precision control of attitude.

The basis for the above proposed revision will be found in Appendix E of this report, where similar recommendations will also be found for lateral acceleration and roll and yaw attitudes during sustained residual oscillation.

3.2.8.6 RSS Pitch Axis Control Power

A. REASON FOR REQUIREMENT

Relaxed static stability, which primarily affects the response of pitch attitude to pitch control input, implies the use of stability augmentation to achieve satisfactory flying qualities. Whereas special

RSS requirements on stability and response dynamics relate primarily to failure state or unaugmented conditions, and hence Level 2 and 3 requirements, the RSS control power requirements are equally or more concerned with augmented characteristics and are applicable to Level 1 as well as Level 2 and 3. Control power requirements, especially for control rate, become more severe with relaxed static stability. The purpose of this requirement is to ensure that there is adequate control margin to prevent divergence and loss of control due to underlying or unaugmented airplane instability for both normal conditions (3.2.8.1 through 3.2.8.5) and those peculiar to relaxed static stability. To this end, it is specifically stated that both normal requirements (3.2.8.1 through 3.2.8.5) and special requirements (3.2.8.6.1 through 3.2.8.6.4) must be met.

B. RELATED MIL-F-8785C REQUIREMENTS

3.2.3.1 to 3.2.3.4, 3.4.2.1.2, 3.4.2.1.3, 3.4.10

C. STATEMENT OF REQUIREMENT

3.2.8.6 RSS pitch axis control power. Control authority, rate, and hinge moment capability have special requirements pertinent to the use of relaxed static stability, both for Normal States (pitch augmentation ON, and unfailed) and Failure States (pitch augmentation OFF or failed) of the flight control system.

The requirements of 3.2.8.1 through 3.2.8.5 shall be met with control authority, rate and hinge moment capability sufficient to provide a safe margin of control, over and above that normally required for stable aircraft, in order to recover from any pitch divergence due to relaxed static stability.

Specific requirements of 3.2.8.6.1 to 3.2.8.6.4 shall be met.

D. RATIONALE BEHIND THE REQUIREMENT

The requirements of 3.2.8.1 through 3.2.8.5 specify that pitch control power shall be adequate to attain prescribed airspeeds and load

factors in the flight envelopes and attitudes for takeoff and landing, with specific trim conditions in some cases. There seems to be no reason for changing the specified performance parameters, trim conditions, or limits except to specifically note and require that these be met with the additional control margin needed to accommodate safely the effects of relaxed static stability. Control rate is generally critical, with hinge moment capability underlying the authority and rate, so all three are specifically called out in the reqirement.

The conditions likely to be critical are approach and landing in turbulence, rolling maneuvers, stalls, and high angle of attack conditions. These are specifically dealt with in subparagraphs 3.2.8.6.1 through 3.2.8.6.4, and include quantitative requirements where possible.

E. GUIDANCE FOR APPLICATION

Since the safe control margin is very much a function of the specific airplane characteristics and task, the contractor should thoroughly examine all possible conditions in the flight envelopes, both for normal and failure states, to ensure that there is adequate control margin for both authority and rate. It must be recognized that without adequate control margin, neither the augmentation system nor the pilot can prevent divergence of an unstable aircraft and consequent loss of control and departure. If any realizable conditions combining instability and inadequate control are found, then either the probability of encountering such conditions must be sufficiently small (extremely remote), or some modification must be made either to provide adequate control margin or to provide a limiter of adequate reliability and effectiveness to prevent the occurrence of the conditions.

The requirements of 3.2.8.1 through 3.2.8.4 must be met with limiters operative. Further, 3.2.8.5 requires adequate control margin to recover from any attainable angle of attack in stalls and all maneuvers.

Paragraphs of 3.2.8.1 through 3.2.8.5 do not directly define required control margins but, rather, state the conditions for which an unspecified but safe margin must be available. Definition of safe margins is the responsibility of the contractor, subject to the specific requirements of subparagraphs 3.2.8.6.1 through 3.2.8.6.4. Though

analysis of trim and steady state conditions can be of help in making comparisons of criticality among the various conditions, meaningful estimates of control power requirements must come from piloted simulation, with subsequent flight test verification carried to the limits of flight safety. In the simulation, aerodynamic and control system characteristics must be represented with fidelity. The simulation must be able to represent the extremes of the envelope for the particular airplane, e.g., stalls, departures, spins, vertical flight, very low airspeeds, and all manner of extreme maneuvers including maximum performance rolls, also failure conditions and transients. The simulation must well represent the control system and actuation characteristics. Simulation of rate characteristics and any factors which affect rate, such as hinge moment, hydraulic flow rate and pressure drop, etc., are especially important since degradation in control surface or system rates can lead to loss of control in both augmented and unaugmented conditions. Control system power requirements are very much a function of stability, being least for neutral stability and increasing substantially for higher levels of static instability (Ref. 33).

F. DEMONSTRATION OF COMPLIANCE

Compliance for 3.2.8.1 through 3.2.8.5 shall be demonstrated as defined for each of these individual subparagraphs. Compliance for 3.2.8.6.1 to 3.2.8.6.4 shall be demonstrated as specified under each of these subparagraphs.

3.2.8.6.1 Minimum Control Authority (RSS Pitch Axis Control Power)

A. REASON FOR REQUIREMENT

Control authority is one of the critical design parameters for airplanes with relaxed static stability. Though 3.2.8.6 places primary responsibility for defining safe margins of control authority upon the contractor, the purpose of this requirement is to define quantitative minimums for certain conditions which are likely to be critical and for which quantitative data on criteria exists.

B. STATEMENT OF REQUIREMENT

3.2.8.6.1 Minimum control authority. For both Normal and Failure States of the flight control systems, the minimum control authority margin over and above the control required for trim, steady maneuvers, and failure transients or conditions shall be as follows for all altitudes, airspeeds, and normal accelerations where the airplane is characterized by relaxed static stability in pitch with control surfaces fixed:____________.

C. RECOMMENDATIONS

Approach and Landing (PA, L)

$$M_{c_{max}} = -.18 \text{ rad/sec}^2 \qquad \text{nose down}$$
$$= .13 \text{ rad/sec}^2 \qquad \text{nose up}$$

where $M_{c_{max}}$ is the pitch angular acceleration available to the pilot and stability augmentation system combined (if augmented) from 1g trim conditions at the appropriate power setting, flap setting, and flight path angle, for the following range of airspeeds:

$$V_{min} \leq V \leq V_{max}$$

The above requirements apply for all Levels (i.e., 1, 2, and 3). The above control power margins shall also apply for steady turns, pullups, and pushovers for load factors ranging from n(-) to n(+) with trim and throttle set for the 1g trim condition.

Wave-Off/Go-Around (WO)
The above requirements for PA and L apply, except thrust shall be at MAT, for all Levels, with all engines and with critical engine inoperative.

Takeoff (TO, CT)

The above requirements for PA and L apply, except thrust shall be at Takeoff thrust, all engines and critical engine inoperative, for all Levels.

Category A, B, and C (other than PA, L, WO, TO, and CT) Flight Phases

The contractor shall define safe control authority margins, for all flight phases and all maneuvers, through analysis and piloted simulation, with subsequent verification in flight test. However, the available pitch control power (to the pilot and stability augmentation system combined) over and above that required for trim and steady maneuvers shall not be less than

$$M_{c_{max}} = -.18 \text{ rad/sec}^2 \qquad \text{nose down}$$
$$= .13 \text{ rad/sec}^2 \qquad \text{nose up}$$

throughout the Operational and Service Flight Envelopes.

Failures

The contractor shall examine all failures which will cause a significant change in pitching moments or pitch trim, and will ensure that there is a safe margin of pitch control over and above that required to control the failure transient. In no case is this margin to be less than

$$M_{c_{max}} = -.18 \text{ rad/sec}^2 \qquad \text{nose down}$$
$$= .13 \text{ rad/sec}^2 \qquad \text{nose up}$$

for all conditions where the airplane is characterized by relaxed static stability with control surface fixed. These requirements apply to all States (normal or failure, augmented or unaugmented) of the flight control system and to all Levels (1, 2 or 3) of flying qualities.

D. RATIONALE BEHIND REQUIREMENTS

Control power or control authority is a determining factor in the design of airplanes with relaxed static stability. The horizontal tail

and pitch control are normally sized by the requirements for nose wheel lift-off at forward c.g. and minimum stability at aft c.g. Other conditions which may be critical are the ability to pull g at high altitudes and airspeeds, especially supersonic ones, for nose-up control, and inverted flight and control at stall for nose-down control.

For airplanes with relaxed static stability, critical conditions are somewhat different. For nose-up control, nose wheel lift-off may still be critical as well as the ability to pull g at supersonic speeds at altitude where the airplane may have strong static stability. For subsonic flight where the airplane is unstable, the primary need for control power is to prevent divergence of the airplane. Critical conditions are likely to be low-speed flight in turbulence, which translates to approach and landing; stall and high angle of attack flight for nose-down control; and inverted flight for nose-up control. In addition, maximum performance rolls may be critical for nose-down control because of inertia coupling (see 3.2.8.6.3 Lessons Learned for F-16 example of loss of control). Since rolling maneuvers and flight at extreme angles of attack are dealt with in 3.2.8.6.2 and 3.2.8.6.3, they will not be considered further here.

For statically unstable airframes, if the pitch control saturates or hits the stop, no more control is available to either the pilot or the augmentation system for stabilizing the airplane and countering disturbances, and loss of control may result. If this saturation occurs in a steady condition (e.g., level flight, turn, pull-up) then loss of control is probable. If it occurs momentarily in a transient condition, where the hard-over control is more than enough to produce a restoring moment which will return the airplane toward an equilibrium or steady condition, then control may be retained. If, on the other hand, the restoring moment is not large enough to arrest and reverse the transient, then divergence and loss of control is assured. Thus, flight safety for RSS conditions depends on having a control margin, over and above that required for trim and steady maneuvering conditions, in order for the pilot or augmentation system to stabilize and counter the effects of disturbances. In this sense, disturbances could be turbulence or discrete gusts, or they could be transients produced by failures (e.g., engine loss, control system failures, battle damage), or they could be

extraneous inputs inserted by the pilot (e.g., remnant, pilot induced noise). This need for extra control margin for RSS conditions is distinctly different from the situation for stable airframes where control stops or saturation can be used as a means for limiting the airplane motions.

Examination of the available literature for data on control power requirements reveals a paucity; what there is deals with nose-down control power required at stall. The simulation experiment (App. B) included an investigation of control power requirements for the approach and landing in moderate and severe turbulence, done by limiting horizontal tail deflection until pilot rating degraded. The criterion values of pitch control power ($M_{c_{max}}$ = -.18 and +.13 rad/sec^2) were the smallest values which caused no degradation in flying qualities (or decrease in PR) for the augmented F-111A airplane with c.g. located to give T_2 = 2 sec for the control surface fixed instability. Comparisons with unaugmented conditions indicate similar requirements for both (augmented or unaugmented), with the unaugmented situation requiring somewhat less control power, if anything. The control surface was limiting during the evaluations, both in maneuvers (severe sidestep in approach) and due to the turbulence, but at the suggested requirement levels the limiting did not degrade flying qualities. Data is provided in the supporting data section.

Since approach and landing in turbulence, especially flare and touchdown, is a critical condition for control authority (especially rate), the control margin requirements determined for this task should be adequate for other tasks throughout the flight envelope for RSS conditions, provided the margins are over and above those required for maneuvers and transients (e.g., failure transients). This assumption should hold for airplanes with control surface fixed instability up to T_2 = 2 sec. For more severe conditions of instability (e.g., T_2 < 1 sec), the margin may have to be increased for all tasks including the approach and landing since the margin is clearly dependent on the unaugmented or control-fixed dynamics (e.g., for very stable aircraft no margin is required). On this basis, the minimum control power requirements determined in the simulation landing have been recommended as requirements for the critical Category C flight phases, approach,

landing, wave-off and takeoff, and are recommended as a floor for other flight phases. To cover special situations where more control power might be needed, and the fact that there is really not enough data, the contractor is given prime responsibility for defining safe control margins for all flight conditions, maneuvers, and airplane states.

A tacit assumption is that satisfactory levels of control margin can be specified in terms of angular acceleration ($\dot{q}$). The assumption may be erroneous, and specification in terms of pitching moment coefficient (ΔC_m), somewhat equivalent to control surface deflection ($\Delta\delta_e$), might be more appropriate. Certainly control for trim and maneuvering is more appropriately defined by the incremental ΔC_m, and also control for configuration and failure transients, thrust changes or engine failures excepted. However, all the available data on control margin required for stabilization, especially for relaxed static stability, are either for approach and landing or for stalled flight. That is, all the data is for low speed flight, at two speeds not very far apart, so there simply is not much basis for the assumption that the additional control margin required for relaxed static stability should be specified as a pitch angular acceleration ($\dot{q}$). The assumption needs to be examined critically, and verified for any specific airplane design.

E. GUIDANCE FOR APPLICATION

The requirements as stated are intended to prevent loss of control of the airplane because control authority is inadequate to contain divergence caused by relaxed static stability, except at extreme angles of attack or in maximum performance rolling maneuvers which are covered elsewhere. Minimum values of control margin are given, based on simulator results (App. B) of approach and landing in a large fighter airplane (F-111A) for the most severe case of instability examined. It is assumed that if these margins, expressed as angular accelerations (rad/sec^2), are applied to all flight conditions, maneuvers and transients, then flight safety will be preserved. Because these assumptions need to be tested, prime responsibility is placed on the contractor for making these tests and for defining safe control power margins for his specific airplane, its intended tasks, and all other

conditions the airplane may be subjected to. This definition requires the use of a high fidelity ground based piloted simulator, with emphasis on fidelity of aerodynamic and control system characteristics and the capability to allow the pilot to exercise the most extreme conditions permissible in airspeed, altitude, normal acceleration, and maneuvering.

For transport airplanes, the approach and landing in turbulence is in all probability critical, but in general, all severe turbulence or gust conditions should be examined, at extremes of indicated airspeed and altitude.

For maneuverable aircraft, especially fighter aircraft, extremes in maneuvering could be more critical than approach and landing. Vertical climb maneuvers to very low airspeeds, followed by roll and yaw inputs, may be critical and should clearly be investigated. High dynamic pressure conditions such as terrain following in turbulence and dives at maximum permissible speed (V_{max}) also need investigating. The more severe failure conditions with respect to pitch trim, and the corresponding failure transients, need investigation as well. Inverted flight may pose critical conditions for nose-up control, especially with a direct pull-up (to the pilot) or "split-S" for recovery.

Control margin and control rate may interact, that is, instability and loss of control may result from the pilot's inability (or that of the augmentation system) to insert an input fast enough, or PIO's may result from too much control system lag. Thus, in simulation tests, what appears to be inadequate control power margin may actually be inadequate control rate, and care should be exercised in simulator testing to separate the two. Control sensitivity and control forces, when sensitivity is too small or forces too high, may also interact with control power requirements, and care should also be exercised to separate these effects. Also, both deflection and rate limits are affected by high hinge moments so these need to be treated with care.

F. DEMONSTRATION OF COMPLIANCE

Demonstration of compliance and flight safety with respect to the adequacy of control power margin requirements is through analysis, high fidelity piloted ground simulation, and flight test verification.

Analysis should show control power margins for all flight conditions and steady maneuvers, and failure conditions as well as any normal state configuration changes involving large pitch trim changes. This analysis will pinpoint the more critical conditions to be examined, and will show the available control margins for stabilization and control of maneuver dynamics, transients and disturbances.

Ground simulation, with fidelity in aerodynamic and control system characteristics and all maneuvering capability, should be used to fully explore the permissible extremes of the airplane flight envelope and maneuvering capabilities. Emphasis is placed on simulation, prior to flight test validation, because control margin is critical for airplanes with relaxed static stability (control surface fixed instability), whether augmented or unaugmented. Inadequate control margin can lead to divergence, loss of control, and subsequent loss of the airplane.

Simulation results should be verified with flight test results as they are obtained, to ensure flight safety.

G. SUPPORTING DATA

The simulator experiment of Appendices B and C investigated the effects of parametrically reducing the position limits of the left and right horizontal tails. The horizontal tails provided both pitch (symmetric deflection) and roll (antisymmetric deflection) control. However, since in the landing configuration the spoilers provided the primary roll control except for very small inputs, limiting the horizontal tail deflection only minimally affected roll control. Position limit variations were performed only for the augmented airplane, taking the most aft c.g. or worst case (Configuration AF2), and the results are presented in Figure 1. It is noted that C_{m_0} was adjusted so that trim horizontal tail deflection was zero at the reference landing flight condition.

The data in Figure 1 show that the pilot was surprisingly tolerant of restricted control effectiveness. Degradation in pilot rating did not occur until horizontal tail deflecion was limited to 3^{0} up, or 5^{0} down, even in heavy turbulence. Data points are sparse, so the data are faired using the shape of curve found applicable by Hall and Booth (Ref. 34). Using these faired data, it appears that 5^{0} nose up and 7^{0} nose down were required to provide the pilot with sufficient control effectiveness. The following table translates control deflection into control effectiveness units appropriate for criteria.

δ_h deg	$M_{\delta_h} \delta_{h_{max}}$ rad/sec^2	Requirement for Landing
3	.08	
5	.13	Nose-up minimum
7	.18	Nose-down minimum
10	.26	

The indicated need for larger nose-down than nose-up control authority was generally born out throughout the simulator investigation of landing, and is probably peculiar to relaxed static stability. The data of Figure 1 is for the airplane with augmentation. However, based on the data on effect of rate limits, the augmented case is the critical one. If adequate authority is provided for the augmented case, there should be adequate authority for the unaugmented case as well.

Except for stall and high-angle-of-attack recovery, the only additional information on control power requirements found was in Reference 33, 35, 36, and 15. Crothers (Ref. 33) gives no quantitative requirements, but provides the source for Reference 36.

Stalony-Dobrzanski and Shah (Ref. 35) compare control power requirements for a tailess clipped delta fighter aircraft as obtained from a moving base ground simulator for various critical conditions:

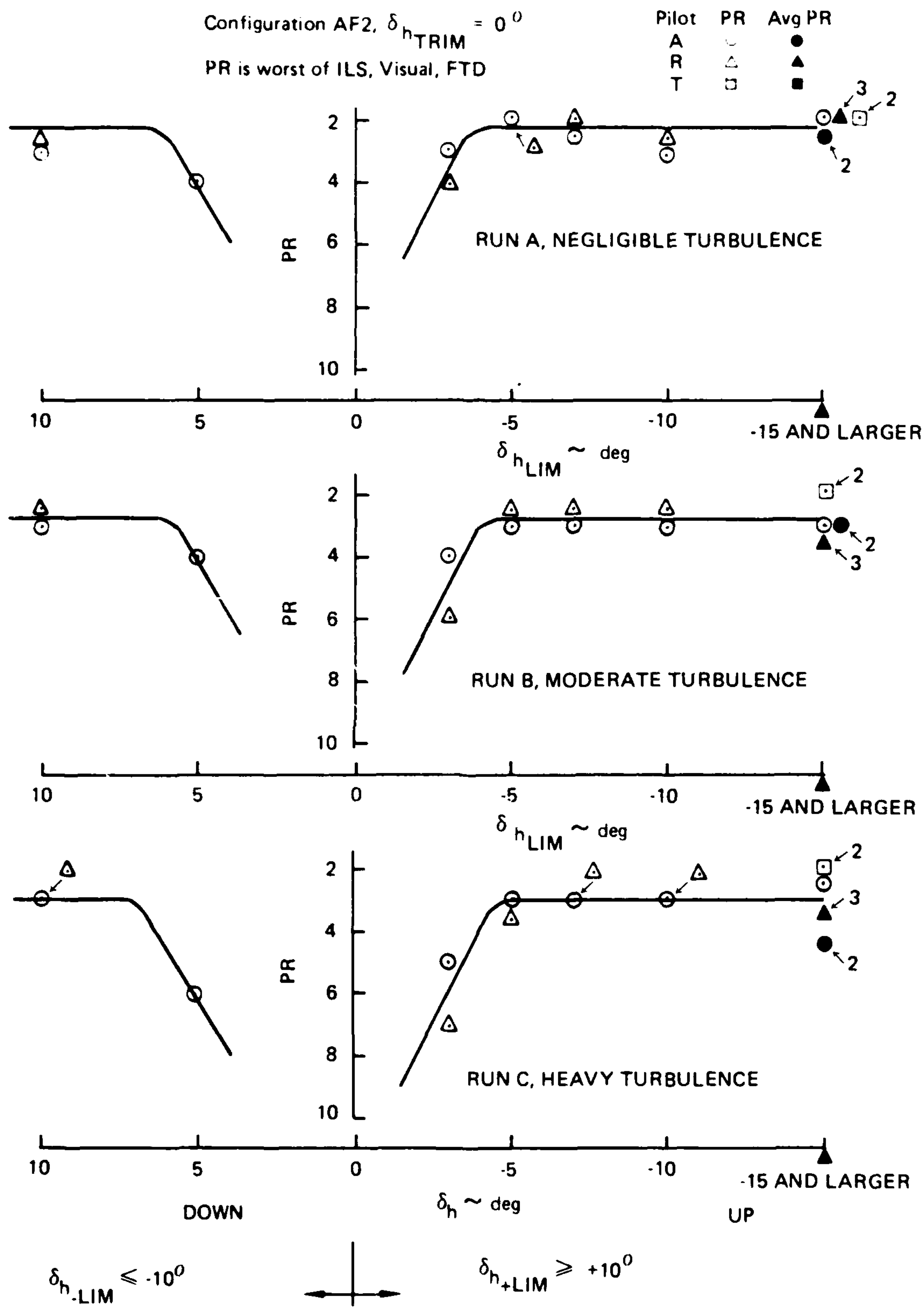


Figure 1 (3.2.8.6.1). Effect of Horizontal Tail Position Limits for Augmented Airplane

1. Limit intensity (10^{-5} probability of exceedance) of turbulence and discrete gusts.
2. Large-amplitude maneuvers, resulting in stall and recovery.
3. Large check-pitch maneuvers used for testing structural integrity.

The longitudinal FCS had pitch rate and normal acceleration feedback, with angle of attack limiting for departure prevention. Control surface authority requirements in turbulence were highest in landing (approach and flare), and were sensitive to airspeed. The authority required for landing was just adequate for stall and subsequent recovery (automatic with pilot opposing it). Generally, control power required was highest for low dynamic pressure with idle power and speed brakes (or max. thrust reverser) and max. control inputs (pitch and roll stick and rudder pedals). The check-pitch structural test maneuvers required authority comparable to that for the large stall recovery maneuvers. For the example airplane, elevon deflections to ±30 degrees (rates to ±90 deg/sec) were required to prevent uncontrolled departures, with landing *in turbulence being equally critical with stall recovery.* Though no means for converting authority and rate requirements to angular acceleration units, or other general airplane characteristics, are given which would allow using the data in quantitative criteria development, knowledge of the general trends is valuable. Particularly, though it is somewhat hard to tell for lack of detail, it appears that Staloney-Dobrzanski and Shah found that a specific control deflection and rate were required (that is, a ΔC_m and rate of C_m) for the various critical conditions rather than an angular acceleration and rate (q and $\dot{q}$).

Watson (Ref. 36) uses analytical methods to examine the gust requirements for a small CCV fighter aircraft based on the YF-16. Results are all for the augmented airplane in power approch, with a discrete (1-cos) shaped vertical gust tuned to the damped airplane short-period frequency. The method was to calculate the response to the discrete gust, with no pilot control input (stick fixed), and only the augmentation system stabilizing and controlling the airplane. The

calculated pitching moment coefficient due to pitch control surface deflection ($\Delta C_m = C_{m_\delta}\delta$), as driven by the augmentation system, was used as a measure of the pitch control power required ($PCP = \Delta C_{m_{max}}$), where

$$PCP_{REQ'D} = PCP_{TRIM} \pm \Delta PCP_{GUST}$$

Watson examines the effect of C_L and C_{m_0}, static margin (SM = 10 to -20%), V_{GUST}, I_y, nonlinear C_m-C_L curves (pitch-up), actuator time constant, rate limit, and resolution on $PCP_{REQ'D}$. He also briefly examines criteria for residual oscillations. Most results are presented as parametric plots of ΔPCP_{GUST} as a function of static margin and other parameters. The baseline case has V_{GUST} = 50 ft/sec, SM = 10%, I_y = 40,000 slug-ft^2. Calculating $\dot{q}_{REQ'D}$ from ΔPCP_{GUST} for this baseline, from data given by Watson, yields

$$\dot{q}_{REQ'D} = 4.54\ \Delta PCP_{GUST} = .61\ \text{rad/sec}^2$$

$$\Delta PCP_{GUST} = \Delta C_m = .135$$

Comparing this control power required with that from the simulation of Appendix B (-.13 to +.18), it is found to be about 3 times as large. As a function of static margin, Watson shows a ΔPCP_{GUST} from .05 for SM = +5% to .19 for -20%, or a range of .23 to .86 rad/sec^2. Several factors may be responsible for Watson's clearly higher control power requirements. First, Watson's results are without pilot, and do not account for the fact that substantial control limiting (control on the stop) can occur before flying qualities are degraded. Secondly, the small YF-16 like airplane may be more gust sensitive than the F-111A baseline of Appendix B. Lastly, the 50 fps gust magnitude is rather extreme for low altitude, for example, MIL-F-8785C shows a 20 fps vertical gust applicable for severe conditions at 100 ft altitude. Also, a time history given by Watson for the baseline case shows α excursions from 1 deg. to 20 deg. during the course of the gust. By not allowing limiting or clipping of control deflection peaks (factor of 2 or 3), and using a larger gust magnitude (factor of 2 or 3), the Watson approach

could reasonably be expected to require 4 to 9 times the control power, and hence the noted difference. The Watson results, though perhaps overestimating the control power required, do present an excellent overview of various effects on the control power required as a function of the degree of relaxation of longitudinal static stability.

Kehrer (Ref. 15) provides some additional data on the control margin required, based on ground simulations of the Boeing SST design in severe turbulence and wind shears, with forward c.g., in the approach and landing. For the landing flare a criterion was developed relating the pitch angular acceleration required to the incremental lift or sink produced by the control input. The criterion from Ref. 15 is presented in Figure 2 with incremental lift or sink normalized by weight as $(\Delta L/W)_{max}$ in acceleration (g) units. A rad/sec² scale has been added to assist interpretation. Since Z_δ was zero in the simulations of Appendix B and C (see Sections B.1.4.1 and C.4.2), the corresponding requirement would be $\Delta Q \sim .04$ rad/sec², much smaller than the $\Delta Q = +.13$ and $-.18$ found required in Appendix B. It is not clear from Reference 15 if the criterion of Figure 2 was critical for the Boeing SST, but if so, perhaps its large pitch inertia reduced sensitivity to turbulence. In any

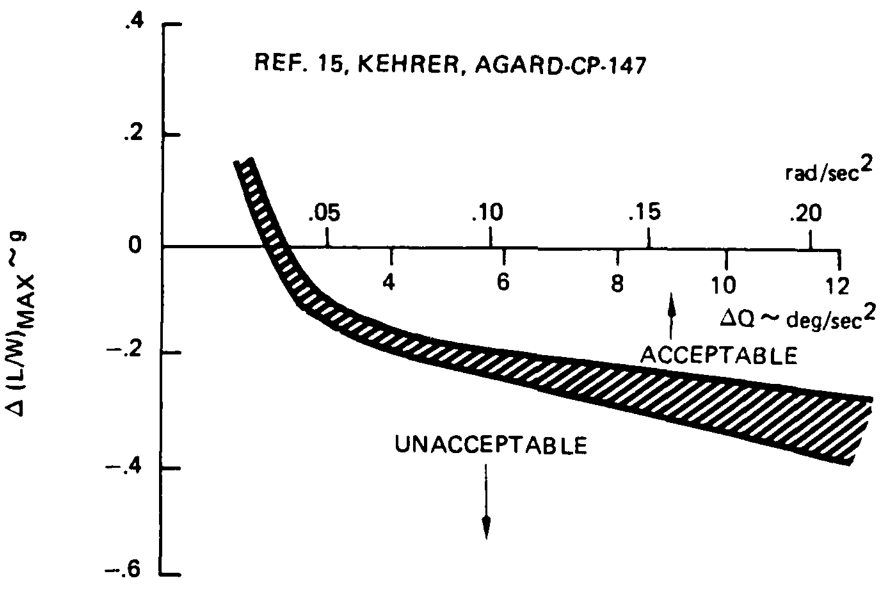


Figure 2 (3.2.8.6.1). Landing Longitudinal Control Requirements

event, the criterion of Figure 2 indicates that for short coupled airplanes with large negative elevator lift, the control power required for flare can be large.

In summary, the approach and landing in turbulence is clearly one of the critical conditions for control power margin for airplanes with relaxed static stability. The herein recommended requirements, though perhaps not large enough for small highly maneuverable aircraft and too large for very large aircraft, do represent a reasonable minimum. Extending the recommended minimums to other flight conditions as an angular acceleration requirement ($\dot{q}$) may not be sufficiently stringent, and an incremental pitching moments requirement (ΔC_m) may be more appropriate. These caveats emphasize the importance of requiring that the contractor develop control margin requirements for his specific airplane design in all conditions characterized by relaxed static stability.

3.2.8.6.2 Minimum Control Rate (RSS Pitch Axis Control Power)

A. REASON FOR REQUIREMENT

Control rate is a critical design parameter for airplanes with relaxed static stability. The minimum required rate will generally be higher than that for stable airplanes. The requirements are for both augmented and unaugmented airplanes, with the required rate for the augmented case more severe, if anything. The consequence of not having a fast enough control system is drastic -- loss of control and possible subsequent loss of the airplane.

The intent of the first part of the requirement is to make the contractor responsible for examining all possibly critical maneuvers at all permissible flight conditions to ensure that loss of control will not occur due to inadequate control rate, either in normal or failure states.

The second part of the requirement treats the known critical condition of approach and landing in turbulence and places quantitative requirements on this condition. It also recognizes that the available control rate may be a function of various airplane failure states, characterized by probabilities of occurrence, and allows an available

rate less than the required rate if the probability of this occurring is sufficiently small. This approach is consistent with the failure state flying qualities requirements of 3.1.11.2.

B. STATEMENT OF REQUIREMENT

3.2.8.6.2 Minimum control rate. The control rate available shall be adequate to avoid causing instability, divergence, or pilot induced oscillations for both normal and failure states of the flight control system, including transients precipitated by control mode changes, store release, and failures. This requirement applies to the prevention of loss of control and recovery from any situation for all maneuvering throughout the permissible flight envelope, including maneuvering appropriate to failure states.

For the critical condition of approach and landing in turbulence, for normal and failure states of and affecting the flight controls, in the atmospheric disturbances specified in 4.0, loss of control due to inadequate control rate shall be no more probable than ____(a)____. Furthermore, for a maximum control input from either the pilot's pitch control or the pitch stability augmentation system, the control surface rate shall provide at least an average pitch angular acceleration rate, measured from trim to full control deflection, of the following ____(b)____.

C. RECOMMENDATIONS

(a) the allowable probability of encountering worse than Level 3 flying qualities of paragraph 3.1.11.2.2, Table 1.

(b) ± 0.9 rad/sec^2/sec for $T_2 \geq 2$ sec. For $T_2 < 2$ sec, a larger minimum available angular acceleration will be required, and the contractor must determine a safe minimum for his airplane using ground based simulation.

D. RATIONALE BEHIND REQUIREMENT

Control rate is probably the most critical design parameter affected by relaxed static stability. The required rate is a function of the degree of instability and the disturbance the airplane is subjected to. However, the level of augmentation (full SAS, back-up SAS, or pilot only) appears to have little to do with the control rate required.

Comprehensive criteria for control rate requirements have not been developed for lack of available data. However, the approach and landing in turbulence is almost always critical for control rates for conventional or stable airplanes, and this also appears to be the case for airplanes with relaxed static stability. The simulator experiment of Appendix B provides some data on control rate requirements for approach and landing in turbulence. These data are used to formulate a quantitative requirement for approach and landing. In addition, responsibility is placed on the contractor to examine all possible critical conditions to ensure that control rates available are adequate in all cases.

More specifically, the first part of the requirement emphasizes the potential special circumstances which may be critical for control rate for any specific airplane design, namely transients, and the instability, divergence, or PIO's that may lead to loss of control and are to be avoided. It specifically calls out both normal and failure states and all permissible maneuvers in the permissible flight envelope. In other words, all possibilities. This all-inclusive approach to control rate requirements recognizes that if control rate proves inadequate in any maneuvers, the result may be loss of control and loss of the airplane, regardless of whether the flight control system is functioning properly or not.

The second part of the requirement, dealing with the critical approach and landing task in turbulence, specifies first that the probability of inadequate control rate shall be on a par with the probability of worse than Level 3 flying qualities. The intent is to recognize that a variety of failures and combinations of failures could reduce the available control rate below the minimum required, and that this is acceptable if its probability is sufficiently low. The recom-

mended value for this probability is $Q_{s(fq)}$ of Table 1 (3.1.11.2.2) which is based on the flight safety requirement of MIL-F-9490D (3.1.7), with default values given in Table 3 (3.1.11.2.2). No relaxation or increase in the probability of an inadequate control rate is allowed with increase in turbulence intensity. A lower limit for the available control rate is specified, based on the results in Appendix B for approach and landing in moderate and severe turbulence (see Supporting Data). The specified control rate (± 0.9 rad/sec^2/sec) is for the augmented airplane (an F-111A) with c.g. set to give a T_2 = 2 sec. for the unstable root with control surfaces fixed. The contractor is made responsible for determining the safe minimum control rate, if $T_2 < 2$ sec, since control rate required is a function of the degree of static instability and possibly other parameters characterizing the airplane.

The results of the simulator investigation reported in Appendix B were obtained by varying the rate limit on the first order actuators ($1/\tau$ = 20 rad/sec) representing the F-111A horizontal tail actuators. Since there is no time delay in the buildup of rate for a first order system, then for a large enough input, the control surface would simply drive to the stop at the rate limit. This behavior has been translated to the requirement as the "average rate from trim to full control deflection for a maximum input".

In addition, the Appendix B data (see Supporting Data) does not show a large increase in control rate requirements going from moderate to severe turbulence. Also, the degradation in pilot rating is extremely abrupt once control rate is found inadequate (generally goes to PR = 10, unflyable). For these reasons, a single minimum control rate (± 0.9 rad/sec^2/sec) is specified for approach and landing, for all flying qualities Levels and all States (normal or failure), with no degradation allowed with turbulence intensity. Also, the control rate required for landing in severe turbulence has been found equal to that required for other critical conditions (see Supporting Data and Ref. 35), thus further supporting the use of a single value as a "floor" in the specification.

E. GUIDANCE FOR APPLICATION

Application of the requirement, as stated, places primary responsibility on the contractor for ensuring that the available control rate is high enough to avoid instability, divergences, or PIO's which would lead to loss of control. The approach parallels that needed to meet requirement 3.2.8.6.1 for minimum control authority, and is based on tests performed in a high-fidelity piloted ground simulator.

Critical conditions for control rate are likely to be low-speed flight in turbulence and stall recovery. However, large transients due to configuration changes and failures also need to be tested, as do any conditions where control rate is reduced due to failures, high hinge moments, or other special circumstances, especially when these coincide with low speed flight in turbulence.

F. DEMONSTRATION OF COMPLIANCE

Demonstration of compliance and flight safety with respect to adequacy of control rate is primarily through high-fidelity piloted ground simulation, verified by flight tests, and should be performed together with the tests for requirement 3.2.8.6.1 on minimum control authority. In addition, analyses are required to show that minimum control rates specified for approach and landing are met with sufficient reliability under failure states.

G. SUPPORTING DATA

The simulator experiment of Appendix B investigated the effect of parametrically varying the actuator rate limits on the flying qualities in approach and landing in turbulence for the F-111A airplane. The left and right horizontal tails provided both pitch (symmetric deflection) and roll (antisymmetric deflection) control. However, since in landing configuration the spoilers provided the primary roll control, except for very small inputs, roll performance was negligibly affected by the rate limits.

Configuration F0: stable, on 8785C Level I boundary

F1: neutral but stable, $T_{1/2} \approx 7$ sec

F6: unstable, $T_2 \approx 6$ sec

PR: Worst of ILS, Visual, FTD

Solid PR (●■) are average ratings

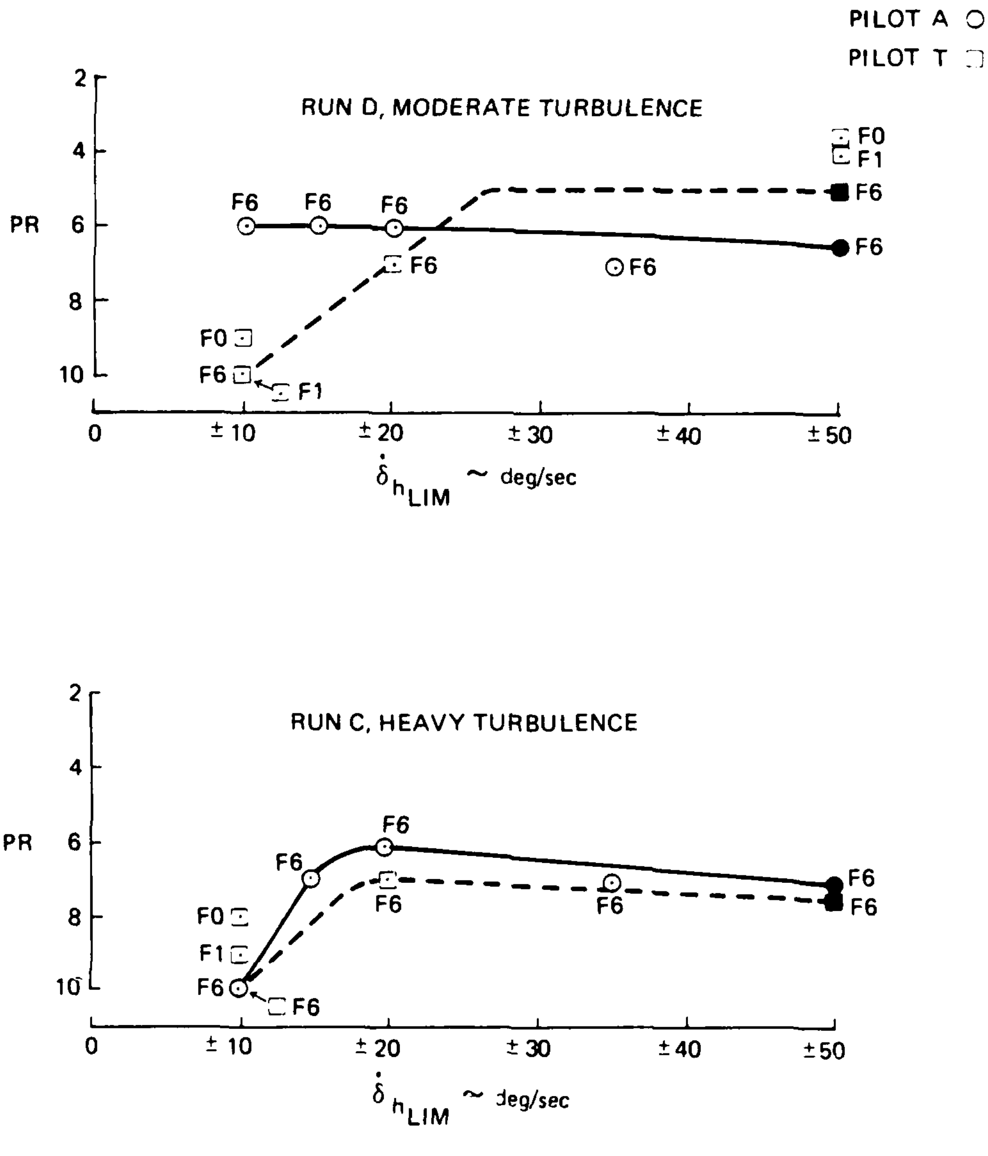


Figure 1 (3.2.8.6.2). Effect of Horizontal Tail Rate Limits, Unaugmented Configurations (F)

Configuration	Control Fixed Stability
AF0	stable, on 8785C Level I boundary
AF1	neutral but stable, $T_{1/2} \approx 7$ sec
AF6	unstable, $T_2 \approx 6$ sec
AF2	unstable, $T_2 \approx 2$ sec

PR: Worst of ILS, Visual, FTD
Solid PR (● ■) are average ratings

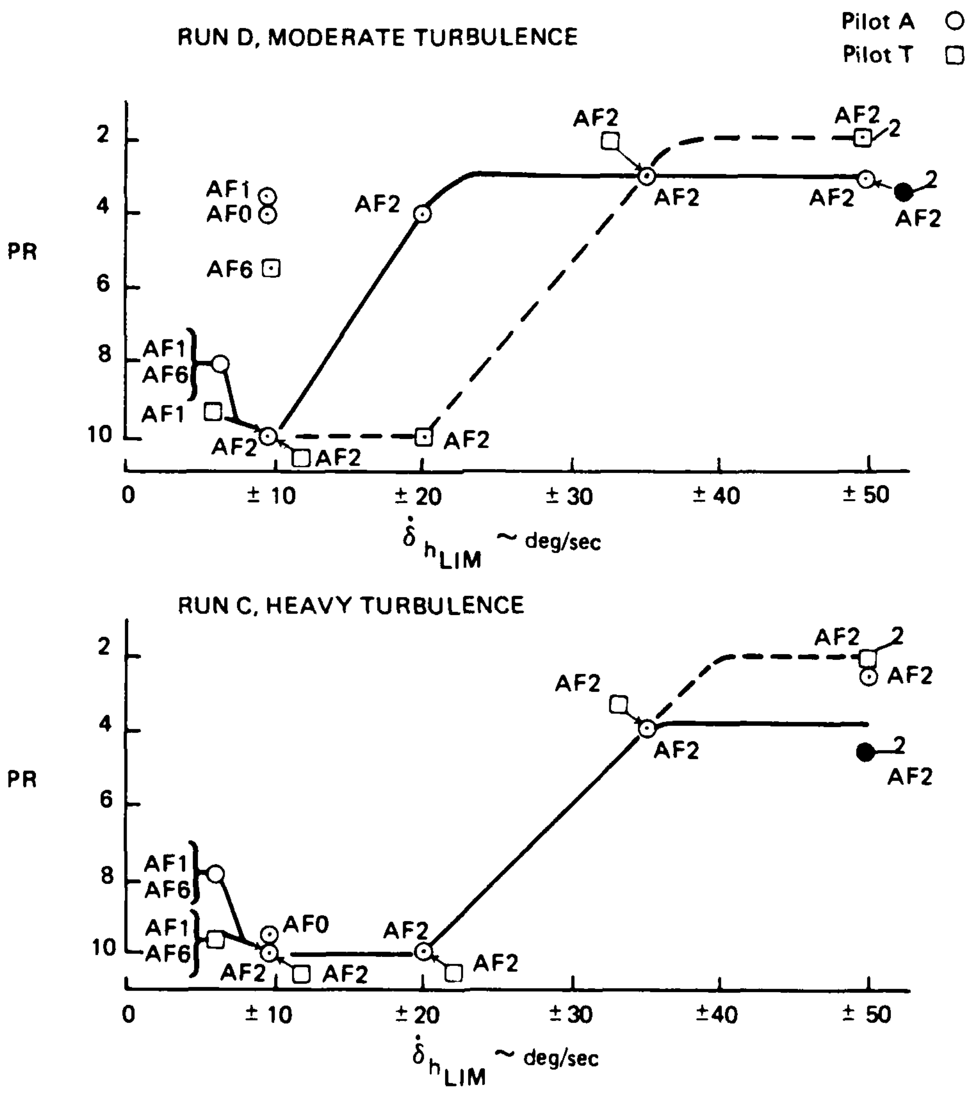


Figure 2 (3.2.8.6.2). Effect of Horizontal Tail Rate LImits, Augmented Configurations (AF)

The effects of varying the horizontal-tail actuator rate limits are presented in Figures 1 and 2 for unaugmented and augmented configurations, respectively. The unaugmented evaluations were performed primarily for the F6 configuration (Figure 1). The data indicate that a rate limit of at least 20 deg/sec is required to avoid degradation in pilot rating. Pilot A accommodated a rate limit of 10 deg/sec in moderate turbulence without degradation, but Pilot T found 10 deg/sec unflyable for F6, also F1, and F0. This difference is explainable in terms of piloting technique: Pilot A flew very smoothly using continual small inputs; Pilot T was very aggressive and used rapid large inputs. In heavy turbulence, the data from the two pilots agrees closely. The pilot ratings for F1 and F6 at 10 deg/sec are essentially the same, so going from T_2 = 6 sec to $T_{1/2}$ = 7 sec does not relax the rate limit requirement. However, F0 with its fairly good short period does rate better (PR = 8).

The effect of rate limit for augmented configurations is shown in Figure 2 for the full range of F configurations (AF0 to AF2), though the bulk of the data is for AF2, the most severe case. The variation between pilots, and with turbulence intensity, is similar to that for the unaugmented configurations (Figure 1). Pilot A does better at the lower rate limits for moderate turbulence. The data for heavy turbulence indicates no variation in rate- limit requirements, either with stability level or with pilot technique. It appears that a rate limit of 35 deg/sec is necessary to ensure that there will be no degradation in flying qualities. This value is that of the baseline F-111A airplane. Translated into angular acceleration units using M_{δ_h} = -1.505 rad/sec²/rad, the requirement ment becomes:

$$M_{\delta_h} \dot{\delta}_{h_{max}} \geq 0.9 \text{ rad/sec}^2\text{/sec}$$

Viewing the data in Figures 1 and 2 as a whole, the following trends are noted. There is not a large difference in pilot rating between moderate and heavy turbulence (close to severe turbulence of MIL-F-8785C, 3.7.3). The control rate required for stable or near neutrally stable airplanes is similar (F0, F1, F6 or AF0, AF1, AF6), but required control rate increases with significant instability (F2 or AF2). Though trends are somewhat inconsistent, control rate requirements appear more critical

for augmented airplanes than unaugmented airplanes, provided the latter can be safely flown so.

Some data on control rate requirements are given by Stalony-Dobrzanski and Shah (Ref. 35), mostly described already in supporting data for 3.2.8.6.1. They found a rate authority of ±90 deg/sec was required together with ±30 deg of elevon deflection. Critical conditions for rate were approach and landing in turbulence, large maneuvers resulting in stall, and the structural test check-pitch maneuver, all requiring about the same pitch control rate.

Watson (Ref. 36) provides additional data on control rates based on an analytical investigation of relaxed static stability for landing approach which is described in more detail in supporting data for 3.2.8.6.1. Watson concludes that control surface rates of 60 deg/sec are desirable if pitch-up is present, less will be acceptable for stable breaks in C_m vs. C_L.

3.2.8.6.3 Rolling Maneuvers (RSS Pitch Axis Control Power)

A. REASON FOR REQUIREMENT

Rolling maneuvers are critical for pitch control power for airplanes with relaxed static stability, as inertia coupling and engine gyroscopic effects will add to the aerodynamic effect to precipitate divergence. Roll rates, bank angles, and pilot control inputs can be restricted under Failure States of the flight control augmentation system, but not so ordinarily under Normal States, so these latter are the subject of this requirement. Besides the maximum performance rolls of 3.8.1, successive bank to bank rolls need to be examined as these have also proven critical (see F-16 experience in lessons learned).

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.10, 3.4.3

C. STATEMENT OF THE REQUIREMENT

3.2.8.6.3 Rolling maneuvers. In the rolling maneuvers specified in 3.8.1, and for at least __________ successive maximum-performance bank to bank rolls between __________ and _______ degrees of bank angle, entered from the same conditions specified in 3.8.1, the control authority, rate, and hinge moment capability shall be sufficient to prevent divergence or loss of control for Airplane Normal States.

D. RECOMMENDATIONS

Airplane Class	Bank Angles for Successive Rolls	
	Positive	Negative
I, IV	$+60^{\circ}$	-60°
II, III	$+30^{\circ}$	-30°

At least four successive bank-to-bank rolls should be performed, entered from the same conditions as the other rolls of 3.8.1.

E. RATIONALE BEHIND REQUIREMENT

Besides approach and landing in turbulence, maximum performance rolling maneuvers are likely to be especially critical for pitch control power if relaxed static stability is present. The reason is that the inertia coupling and engine gyroscopic effects (for rolls in one direction) will add to the divergent moment due to the unstable aerodynamics. Thus these conditions must be examined critically. In addition, lessons learned from F-16 experience show that the inertia coupling effect in successive bank to bank rolls of modest proportion can build up angle of attack and precipitate divergence. In the case cited in lessons learned for this requirement, the airplane was lost but the pilot ejected safely. The selected bank angles are meant to represent the largest that the pilot might use in rapid wing rocks for signaling or other purposes in operational use. For fighter aircraft, as indicated in lessons learned, wing rocks are used to signal the intention to end and break off air-combat practice. Another fighter use would be for evasive maneuvers in air combat. For larger, less maneuverable aircraft, any

wing rocks used would certainly be less, hence the reduction from 60 to 30 degrees.

F. LESSONS LEARNED

An F-16 airplane was lost as a result of performing successive wing rocks in a 2 to 3g turn at about 6,000 feet altitude and 430 kt. The pilot safely ejected after a sudden pitch-up. The F-16 pilot, Rossetti, with wing-man, was making a practice ground attack, and was attacked by an aggressor F-15. The following excerpts from Aviation Week and Space Technology, March 24, 1980, p. 18, describe the mishap in the pilot's words:

> Rossetti called for a hard left, which became a 5-10 deg. nose-high turn at 4-5g. At that point, the F-15 switched to Rossetti, who said he backed off to about 2g and began rocking his wings, the "universal knock-it-off sign".
>
> "I do about four wing rocks and after about the fourth wing rock and just about the time I'm thinking that's okay, that's enough wing rocking, the airplane very smoothly and positively pitches straight up on me," Rossetti said. "So, I go from a position of slightly nose high, mil [military] power, 2- or 3-g wing rock, to the nose just pitching straight up and the airplane stands on its tail."
>
> He noted that in air-to-air configurations, the F-16 has limiters on angle of attack, yaw, pitch and g forces that allow relatively unrestricted maneuvers with asymmetrical loads.
>
> But, in the air-to-surface configuration, Rossetti said, he thinks his bank-to-bank rolls boosted the angle of attack until it exceeded 12 deg.
>
> "There are two limits that I exceeded," he said. "The first one was the no max command rolls above 12-deg. angle of attack, and

that, as a result, boosted me through the 20-deg. angle of attack, which is why the airplane pitched out of control. What happens with the airplane is that the stabilator is the only thing that keeps your angle of attack under control when you are maneuvering."

"With the static margin being the way it is and things like that, and what happens when you get into high roll rates, is that you have a coupling of the pitch due to roll, aerodynamic coupling, and the stabilator saturates and reaches the point where you are commanding full nose down as you roll and it goes full deflection and it just can't do anymore. But the roll continues to boost the angle of attack so you exceed the ability of the tail to hold the angle of attack within limits."

"Now, we knew this continuous roll thing. One of the things I was not aware of was that a repeated bank-to-bank roll would do the same thing to you; that everytime I banked the angle of attack went a little bit higher, and a few of these just brought it to the point where it went out of control as it exceeded the tail's ability to hold it down to 28 deg."

3.2.8.6.4 <u>Stall and High Angle of Attack (RSS Pitch Axis Control Power)</u>

A. REASON FOR THE REQUIREMENT

Stall and high angle of attack flight are most likely to pose the critical conditions for pitch control power for any airplane with relaxed static stability. If the airplane enters stall with insufficient control power to recover, then it will diverge to higher angles of attack, especially if there is any pitch-up, and recovery will be impossible. Thus it is mandatory that statically unstable airplanes have adequate control power for prompt recovery from stall, and that this control power be maintained to very high angles of attack. This means that the airplane must have a stable break in the pitching moment curve near stall as well as adequate recovery control up to the break.

Alternatively, if the airplane does not have a natural pitch-down tendency at stall, then a highly reliable limiter system must be provided which will prevent the airplane from reaching angles of attack from which recovery is not possible. This limiter must have flight-safety type reliability and effectiveness.

The intent of this requirement is then to prevent loss of control of the aircraft resulting from entry into stall and high angle of attack flight.

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.2.1.2, 3.4.2.1.3, 3.4.2.2, 3.4.2.2.1, 3.4.2.2.2

C. STATEMENT OF REQUIREMENT

3.2.8.6.4 Stall and high angle of attack. In any Airplane Normal State or Failure State of 1.6.1 or 1.6.2 within the Permissible Flight Envelope, for all angles of attack from zero lift to ___(a)___, with full nose-down control the airplane shall exhibit a net nose-down pitching moment of sufficient magnitude to generate ___(b)___ rad/sec^2 nose-down angular acceleration.

Alternatively, a lesser nose-down (including nose-up) pitching moment shall be allowed at high angles of attack if a means or device is provided to limit the angle of attack, with sufficient reliability, to values below those where the above requirement for angular acceleration is not met. The probability of an angle of attack limiter failing to work shall be less than ___(c)___.

The same angular acceleration requirement applies for nose up pitching moments for negative angles of attack from zero lift to ___(d)___ with full nose up control. An alternative limiter of sufficient reliability is also allowed to help meet this large negative angle of attack requirement.

D. RECOMMENDATIONS

(a) 90 degrees or the structural limits

(b) a nose down angular acceleration ($\dot{q}$) at V_s of the following magnitude

Class	$\dot{q}$, rad/sec^2
I	-.28
II	-.20
III	-.08
IV	-.28

Alternate: a nose down angular acceleration ($\dot{q}$) at V_s given by the following equation

$$\dot{q} = -1.7\ (I_y)^{-0.11} + 0.2 \qquad I_y \text{ in slug-ft}^2$$

but in no case less than -.08 rad/sec^2.

(c) the allowable probability of encountering worse than Level 3 flying qualities of paragraph 3.1.11.2.2, Table 1.

(d) -90 degrees or the structural limits

V_s is the 1g level flight stall speed.

E. RATIONALE BEHIND REQUIREMENT

Recovery control in stalls and at high angles of attack is of immense significance to the design of airplanes with relaxed static stability. The instability limit and the aft c.g. limit will likely be set by the longitudinal control available to pitch the airplane nose down at high angles of attack. This capability is mandatory to prevent the airplane from entering a deep stall from which no recovery is possible. Either there must be sufficient aerodynamic nose-down control to recover from all angles of attack, or an angle of attack limiter with flight-safety type reliability must be incorporated which will prevent the airplane from attaining angles of attack where nose down control is inadequate.

The requirement for control, and its relation to static instability is illustrated in Figure 1 for a typical modern high performance airplane. The upper figure (a) shows an airplane with c.g. too far aft and too unstable for the available control power. If the airplane ever reached 20 deg angle of attack, the airplane would pitch up out of control with no means to recover, might well lock into a stable deep stall above $\alpha = 60^0$. With the static instability shown, and with stall near or at $\alpha = 20^0$, the probability of reaching that α due to turbulence is likely. Even an α limiter would not solve the problem, since to provide adequate margin for maneuvering and disturbances, the limit would have to be so low that performance would be severely compromised.

The lower figure (b) shows a more forward aft c.g., with control power now meeting the minimum requirement slightly above stall at about $\alpha = 25^0$. The pitching moment now goes stable above the stall, but then pitches up again as α approaches 40 deg. Without this pitch-up, the airplane would probably have satisfactory inherent characteristics at high angles of attack as almost any airplane configuration will have strong nose-down pitching moments as α approaches 90^0. However, as shown in Figure 1(b), control power reaches the minimum allowed at $\alpha = 45^0$, and at $\alpha = 50^0$ an uncontrollable pitch up would again occur. Accordingly, an α limiter must be provided which will insure that the airplane can never reach an angle of attack larger than 45^0, that is, with a probability less than that required for flight safety or the allowable probability of aircraft loss due to flying qualities or flight control failures.

The recommended control margin requirement for high angles of attack extends from 90^0 to -90^0. For fighter aircraft which go through extreme maneuvers, including vertical flight to very low airspeeds, the reason for extending the control margin requirements to all possible angles of attack is readily understandable. But the rationale for applying this criteria to all aircraft, including the large Class III aircraft, is not so apparent. The wording could be changed to "all attainable angles of attack". However, all aircraft are flown at moderately high angles of attack at various points in their flight envelope, in landing, maneuvering, or cruise, and they are all subjected

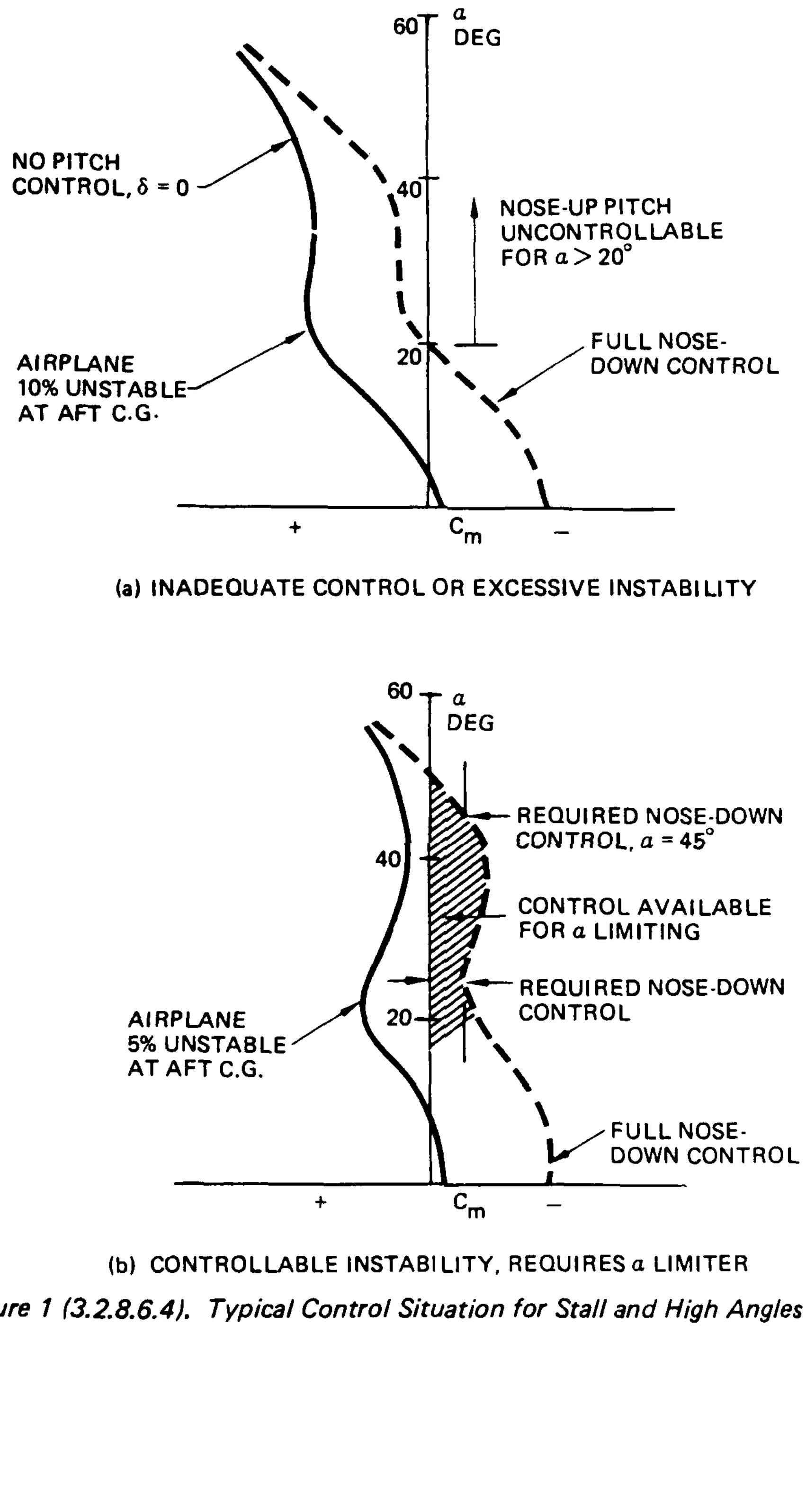


Figure 1 (3.2.8.6.4). Typical Control Situation for Stall and High Angles of Attack

to turbulence including occasional severe turbulence and gusts. Large transient angles of attack, well above stall, do occur occasionally for all aircraft. These transients must not precipitate loss of control with no possibility of recovery. An excellent discussion of high-angle-of-attack control requirements is given by Kehrer (Ref. 16) which greatly expands on the foregoing.

Some quantitative data exists on control power requirements at stall applicable to airplanes with relaxed static stability, mostly simulator data but some flight test data. Chalk (Ref. 23) provides a recent summary of the data available, emphasizing SST experience applicable to the NASA Supersonic Cruise Transport. Chalk arrives at the following criteria:

Level 1	$\ddot{\theta} \leqslant -.08$ rad/sec^2
Level 2 and 3	$\ddot{\theta} \leqslant -.05$ rad/sec^2

These criteria come from Reference 37, p. 11, and are cited as coming from recent unpublished studies. Chalk further cites records from Concorde SST flight tests that show pitch accelerations as high as $\ddot{\theta}$ = -.055 rad/sec^2 in stall recoveries.

Sudderth (Ref. 22) provides the most comprehensive data, taken in the NASA FSAA simulator using the Boeing SST (2707-300PT) model. Sudderth varied the control power available at stall for various levels of turbulence, and obtained pilot ratings for stall recoveries. The pilot rating data is shown in Figure 2, with cross plots of the data in Figure 3 for PR = 3.5 and 6.5, considered by Chalk (Ref. 23) as the boundaries for satisfactory and acceptable, respectively.

Urie (Ref. 38) has collected a substantial body of flight test data on stalls for three Lockheed airplanes and analyzed this data for the maximum nose-down angular acceleration used. The airplane and number of stall recoveries included were as follows:

S-3A	64 stalls, 29 in landing configuration
L-1011	265 stalls, 93 in landing configuration
C-5A	41 stalls, all in landing configuration

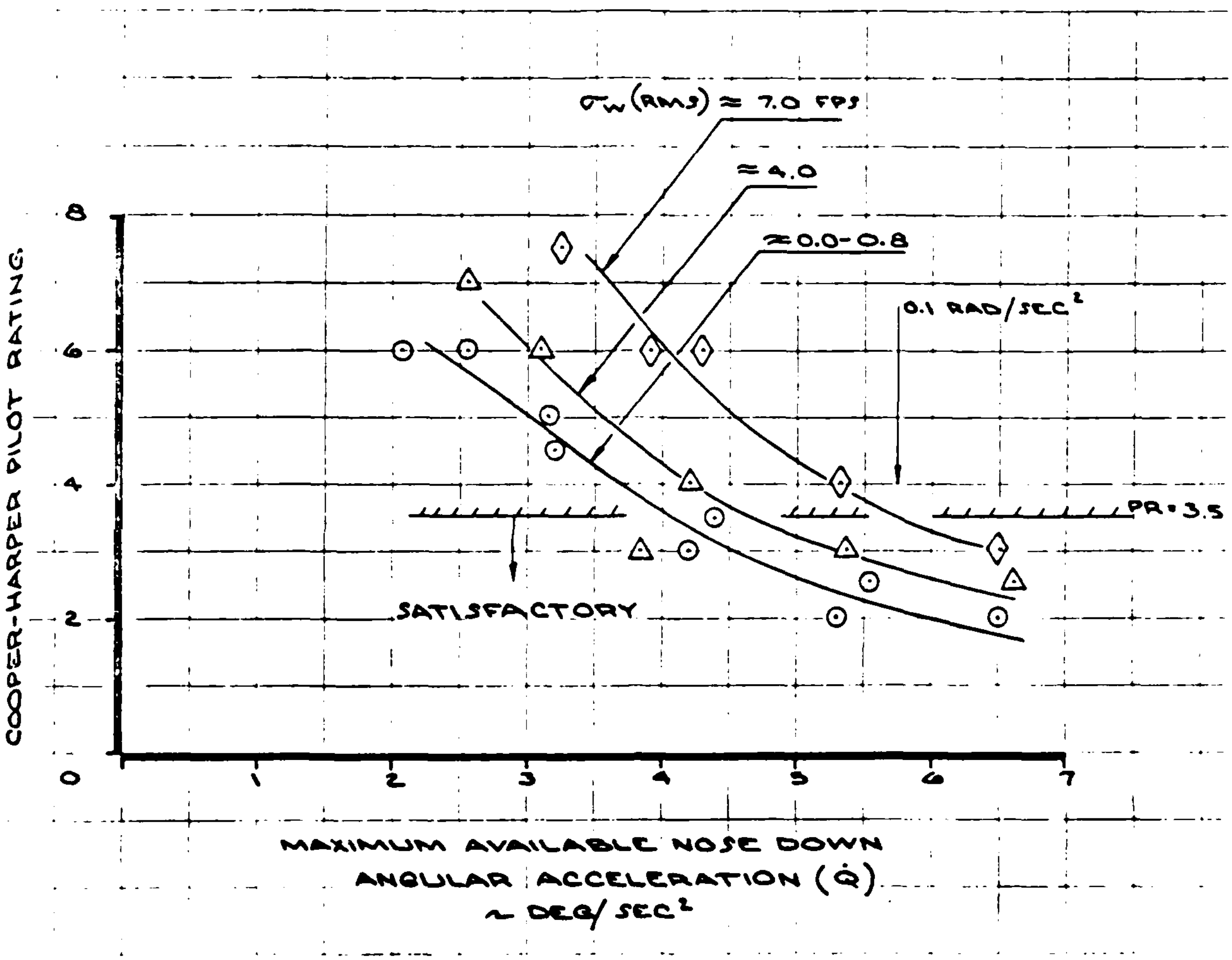


Figure 2 (3.2.8.6.4). Stall Recovery Control Power Evaluations (Ref. 22, Sudderth, et al.)

Urie's plot for the L-1011 of the probability distribution of angular acceleration is presented in Figure 4(a), and the 90% level for the 3 airplanes is plotted in Figure 4(b) vs I_y for landing configuration stalls and for all stalls. Urie notes that in no case was the full nose-down control used for the L-1011, so the measured values of $\ddot{\theta}$ were always enough to satisfy the pilot. Urie's explanation of the difference between the two curves of Figure 4(b), that it is due to nose-down moments from the flaps, seems unsatisfactory. Rather, the airspeed was lower for landing flaps than for partial flaps, so larger control deflections and hence larger forces were required of the pilot to

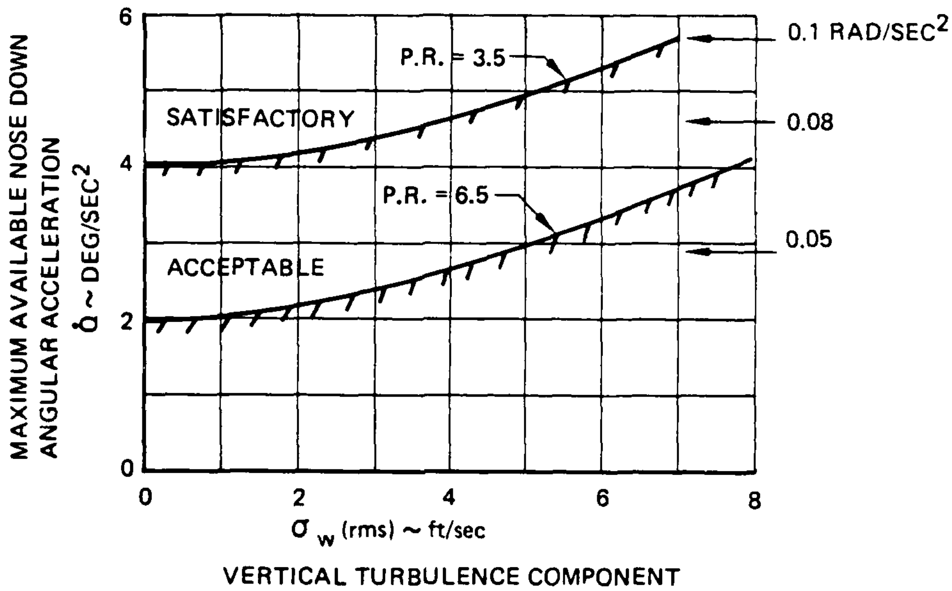


Figure 3 (3.2.8.6.4). Stall Recovery Control Power as a Function of Turbulence (Ref. 22, Sudderth et al.)

generate the same $\ddot{\Theta}$ in landing configuration, and the pilots just didn't push any harder.

The distribution for the L-1011 (Fig. 4(a)) indicates that the 90% exceedance level is $\ddot{\Theta}$ = -.08, but the largest usage was $\ddot{\Theta}$ = -.04 rad/sec^2. This might logically translate into a satisfactory (PR = 3.5, Level 1) requirement of -.08, and an acceptable (PR = 6.5, Level 2) requirement of -.04. These values agree closely with Sudderth's in Figure 3, also the Grantham, et al. (Ref. 37) values (-.08, -.05). Sudderth gives no inertia data in Reference 22, but for the Boeing 2707-300 at the given weight $I_y = 3.7 \times 10^7$. Grantham gives $I_y = 5 \times 10^7$, though there is no assurance that this value corresponds to the unpublished data credited for the criterion values.

The above described data are the basis for the recommended requirements. For large aircraft, with pitch inertia on the order of 10^7 to 5×10^7 slug-ft^2, an acceptable nose-down angular acceleration of -.08 rad/sec^2 seems fairly well established. Urie's data indicate more nose-down acceleration is required as inertia or airplane size decreases. But this trend is probably more closely related to type of airplane and degree of maneuverability than inertia. Urie's curve for

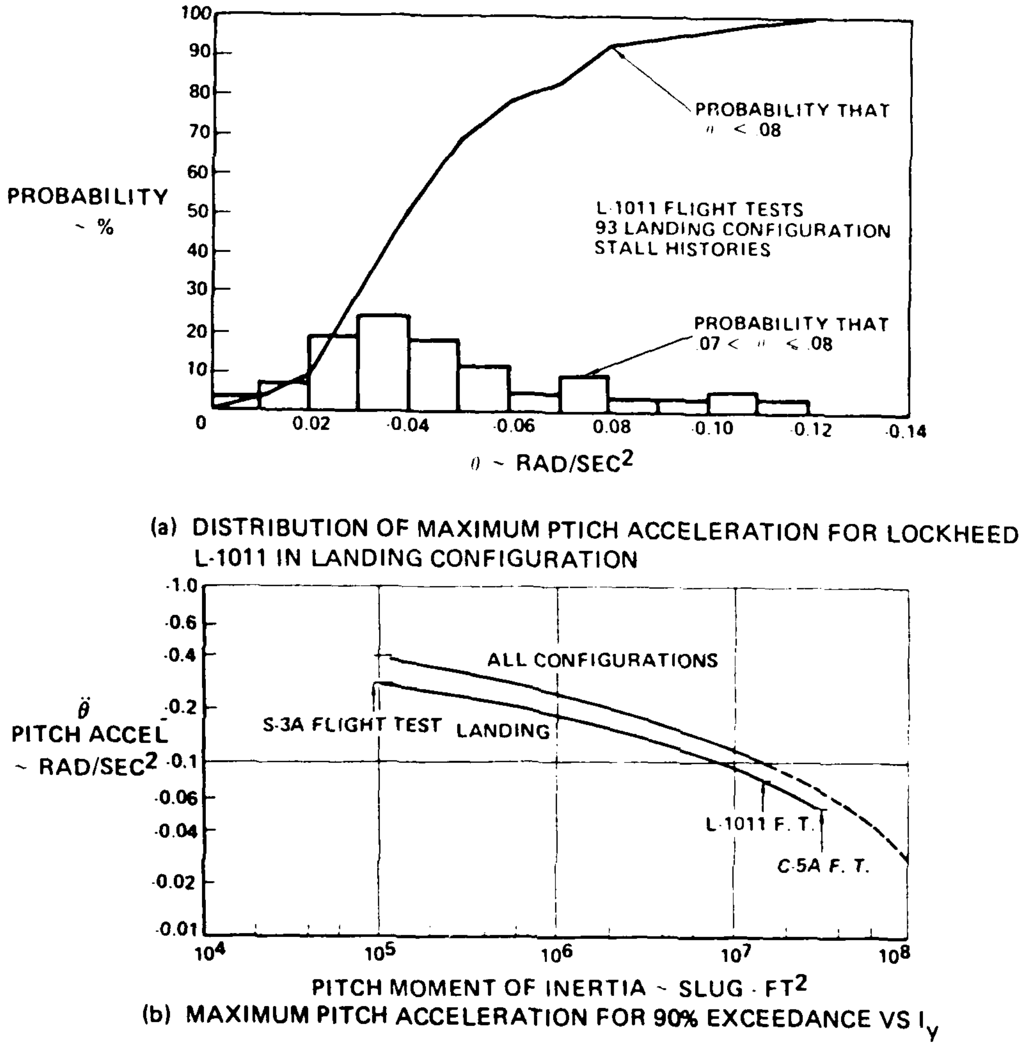


Figure 4 (3.2.8.6.4). Maximum Nose-Down Angular Acceleration Used for Lockheed S3A, C-5A, L-1011 (Ref. 38, Urie, AGARD-CP-260)

landing in Figure 4(b) has been used to specify the requirements for small aircraft, using inertias of 10^5 for Class I and IV, and 10^6 for Class III, based on trends for moments of inertia published in Reference 39 (p. 2.12). Urie fits the upper line in Figure 4(b) with the following expression.

$$\ddot{\Theta} = -3(Iy)^{-0.14} + 0.2 \qquad I_y \text{ in slug-ft}^2.$$

The expression given as an alternate in the recommendations fits the lower landing configuration line closely. Using the alternate criterion

allows specifying the nose-down acceleration requirement as a function of I_y rather than airplane class, but ought to produce similar results.

As an additional data point, not specifically derived from stall recovery tests, the landing simulation investigation of Appendix B arrived at a requirement in severe turbulence for nose-down pitch control margin as follows:

$$\ddot{\theta} = -.18 \text{ rad/sec}^2$$
$$I_y \approx 3\text{x}10^5 \text{ slug-ft}^2$$

This compares with $\ddot{\theta} = -.24$ from the lower curve of Figure 4(b) for the same I_y. In Reference 35, it was found that stall requirements and approach and landing requirements in turbulence were about equal. This comparison then somewhat validates the trends in Figure 4(b).

No degradation in control power with Level of flying qualities is allowed for in the recommended requirement because of the critical nature of nose-down control power margin for high angles of attack. However, the L-1011 data in Figure 4(a) shows that $\ddot{\theta} = -.04$ would give 50% coverage, $\ddot{\theta} = -.05$ would give 70% coverage. The Sudderth and Grantham data suggest $\ddot{\theta} = -.05$ as appropriate for Level 2. Reducing the requirements a proportionate amount, for each class or as a function of I_y, would not be unreasonable. More data are clearly needed, especially for Class I, II and IV airplanes.

It should be noted that the requirement for nose-down control margin at stall and high angles of attack is not affected by the level of stability augmentation. For unstable airplanes, this margin is the last resort for recovery from divergence to high α. The only form of augmentation that relates directly to the requirement is an angle of attack limiter. If the α limiter is required because the control margin does not extend to all attainable α, then its reliability must be equivalent to flight safety requirements as recommended.

F. GUIDANCE FOR APPLICATION

The requirement defines a minimum nose-down pitch control power margin at stall and high angles of attack (also negative stall and α)

based on the pitch angular acceleration ($\dot{q}$) at stall (V_s) in 1g level flight. For higher speeds in accelerated stalls, it is not clear whether the same angular acceleration or a higher one is needed. The tacit assumption is made that the angular acceleration requirement will be translated into a pitching moment coefficient margin (ΔC_m). With this interpretation, based on the available data it appears that the margin should be adequate to handle most exigencies, including accelerated stalls and rolling maneuvers. However, it is clear that stall and high angle of attack flight pose a sufficiently complex problem, subject to specific airplane design details, that a thorough investigation must be made of the adequacy of pitch control margin at all critical conditions. A comprehensive investigation using high fidelity ground based simulation is required, ultimately validated by flight test.

If the required control margin is not maintained throughout the high angle of attack range, and an angle of attack limiter is required to meet the specification, then the limiter must be designed to handle all possible inputs and conditions which would precipitate pitch divergence to high α. Possibilities include pilot inputs and turbulence in level flight stalls and in accelerated stalls from pullups and turns, the rolling maneuvers of 3.2.8.6.3, and vertical flight to very low airspeeds with pilot inputs in pitch, roll and yaw; also any condition that would produce high sideslip angles at high α. General references to α limiter design and development are References 40 and 35, with YF-16 and F-16 experience described in References 41 and 42, and more detailed references given in each of the foregoing.

If the α limiter is required to meet high α pitch control margin requirements for stall, then its reliability must meet flight safety requirements. However, an α limiting function might be provided in a departure prevention system designed to allow the pilot head-up and out-of-the-cockpit flying with unlimited restriction on control motion and maneuvers, even though the pitch control margin is adequate without the limiter. In this case, less than flight safety reliability is allowed provided the departure preventer is fail safe.

G. DEMONSTRATION OF COMPLIANCE

Analytical demonstration of compliance with control margin requirements must be based on wind-tunnel data to high angles of attack.

Demonstration by simulator is to show that the available pitch control margin will provide safe recovery from stalled flight, and any attainable high angle of attack conditions.

Satisfactory safe recovery from stall is to be demonstrated in flight tests, with validation of analysis and simulation as one objective.

If the pitch control margin for stall is met by virtue of an angle of attack limiter, then demonstration by simulator is required to show that the limiter functions satisfactorily under all probable conditions of pilot input, turbulence, and maneuvers. Subsequent flight tests to validate limiter operation are required. Vertical flight to negative airspeeds (tail slide) is not a requirement, but safe and ready recovery from this condition is desirable.

3.2.9.3 Pitch Axis Control Forces - Variation with Speed

Separate requirements apply to pitch control force variations with speed for slow changes in speed in steady-state equilibrium flight (3.2.9.3.1) and rapid speed changes (3.2.9.3.2).

For conventional airplanes with minimum augumentation (e.g. rate dampers) or none, the control force gradient with speed in equilibrium flight is a measure of the airplane's static stability, with some stability desirable as indicated by a stable or negative gradient. For highly augumented aircraft, the desired stability may be provided by the augmentation system independently of the pitch control force gradients. However, it is also desirable to minimize the amount of trim the pilot must apply in making speed changes and executing mission profiles. Though the desired stability is covered under other requirements, principally 3.2.1, 3.3.1.2, and 3.4.1, there is still a need to delimit the pitch control force gradients with speed in unaccelerated flight (3.2.9.3.1).

During rapid speed changes, the changes in pitch control-force with speed can be affected by thrust or the propulsion system, deceleration devices, configuration changes, and transonic effects. These control force changes, quite apart from the force gradients with speed in unaccelerated flight, must not interfere with the pilot's ability to control or maneuver the airplane while undergoing rapid speed changes (3.2.9.3.2).

3.2.9.3.1 Pitch Control Force Variation with Speed on Unaccelerated Flight

A. REASON FOR REQUIREMENT

With the airplane trimmed, it is desirable that it exhibit speed stability, but at the same time it is desirable to minimize the amount of trim the pilot must apply in executing mission tasks. Changes in trim with speed result from conventional static stability, variation of pitching moment with speed (Mach no. or thrust moment effects), or from configuration changes (c.g., wing sweep, flaps, camber, etc.) which may be automatically scheduled to improve performance. It is therefore desirable to establish design criteria for control force gradients and changes from trim that occur within a speed range about trim.

B. RELATED MIL-F-8785C REQUIREMENT

3.2.1

C. STATEMENT OF REQUIREMENT

3.2.9.3.1 Pitch control force variation with speed in unaccelerated flight. With the aircraft trimmed in unaccelerated flight at any speed and flight path angle, with throttle and trim not changed by the pilot, the variation of control force with speed shall be smooth. For speed changes from trim of ±15%, except the change need not exceed ±50 knots calibrated airspeed, ±0.1M, or the boundaries of the Service Flight Envelope, the following requirements shall be met_____________.

D. RECOMMENDATIONS

Table 1 (3.2.9.3.1)
Pitch Control Gradient Limits

		Stick Controller		Wheel Controller	
		max	min	max	min
Level 1	lb/knot	0	-0.4	0	-0.9
Level 2	lb/knot	0.7	-0.7	1.4	-1.4
Level 3	lb/knot	1	-1	2	-2
Level 1	lb/.01M	0	-2.5	2	-5.5
Level 2	lb/.01M	4	-4	8.5	-8.5
Level 3	lb/.01M	5.5	-5.5	12	-12

Table 2 (3.2.9.3.1)

Maximum Control Force Change in Specified Speed Range

		Stick Controller	Wheel Controller
Level 1	lb	16	34
Level 2	lb	23	50
Level 3	lb	35	75

Note: The control force gradients are per knot CAS. Negative gradients indicate stability.

E. RATIONALE FOR REQUIREMENT

The gradients of cockpit pitch control position and force with airspeed in equilibrium flight are measures of stick fixed and stick free static stability for unaugmented airplanes or ones with relatively simple augmentation systems. However, for higher levels of augmentation (e.g., attitude or airspeed feedback and control) the speed stability, dealt with under Section 3.4.1, may not be related to pitch control gradients. There is a need to specify limits on these gradients with airspeed, since if too large, the forces interfere with the pilot's ability to fly the airplane in maneuvers or perform various mission tasks. For Level 1, a zero control force gradient with speed is desirable in some cases, e.g., tracking a target during a dive as in dive bombing or ground attack. Otherwise, a stable gradient (negative F_s/u, push for an increase in speed) is desirable. Chalk in Reference 3 discusses the need for limits on F_s/u, based partially on some Swedish data, then updates the discussion in Reference 23 based on FAA and French data relative to the SNIA/BAC Concorde SST and F-4 data. The recommended requirements are essentially those of Reference 23.

In transonic flight, large changes in pitching moment with speed (M_u) can cause large stable and unstable (negative and positive) gradients in F_s/u. These can cause piloting difficulty, and MIL-F-8785C in 3.2.1.1.1 places limits on the force gradient and the

maximum force for transonic operation, allowing unstable F_s/u. The requirements of 3.2.1.1.1 (MIL-F-8785C) could be stated in terms of Table 1 and 2 with little change by relaxing the Level 1 force gradients to the values for Level 2 in Table 1, and retaining the rest of Table 1 and Table 2 requirements as is.

F. GUIDANCE FOR APPLICATION

The gradient, F_s/u, for airplanes with small or zero M_w, is related to the stick force per g, F_s/n, by the following approximation (Ref. 3) for unaugmented airplanes.

$$\frac{F_s}{u} = + \frac{V}{g}\left(\frac{M_u}{M_q}\right)\left(\frac{F_s}{n}\right)$$

So requirements for F_s/u are not necessary except where aerodynamic effects (M_u), flight control system characteristics, or configuration changes produce an F_s/u independent of F_s/n. The requirements in Table 1 and 2 provide rather considerable latitude, but zero or small gradients and forces are desirable and should serve as objectives. Since characteristics that might be objectionable to the pilot tend to be highly task and airplane dependent, assessment of conditions where these gradients are high should be performed using ground base piloted simulation.

G. DEMONSTRATION OF COMPLIANCE

Analysis, based on wind tunnel data, can be used to show compliance with the specific requirements for gradients and forces.

Ground simulation should be used to demonstrate satisfactory design for critical conditions.

Analytical and simulation results should be validated by flight test.

H. SUPPORTING DATA

Supporting data will be found in References 2, 3, 5, and 23.

3.2.9.3.2 Pitch Control Force Variation During Rapid Speed Changes

This requirement is 3.2.9.3 of Reference 18, renumbered to allow its incorporation with new requirement 3.2.9.3.1 under 3.2.9.3. No change is required except the number and the title is shortened by deleting the word "axis".

3.2.9.9 RSS Pitch Control Forces

3.2.9.9.1 RSS Pitch Control Forces in Unaccelerated Flight.

A. REASON FOR REQUIREMENT

For the flight control system in Normal State there are no special requirements for relaxed static stability (RSS) and the objective of the first part of this requirement is to explicitly state so. For Failure States, with relaxed static stability the pilot flies the airplane differently than he would if it were stable, and special requirements apply to the control force gradients and changes with airspeed. The objective of this requirement is to insure that control force levels are examined appropriately and objectionable force levels are avoided.

B. STATEMENT OF REQUIREMENT

3.2.9.9.1 RSS pitch control forces in unaccelerated flight. For flight control system normal states (augmentation ON, unfailed) the requirements are unchanged from 3.2.9.3.1. For flight control system Failure States (augmentation OFF or failed) no control force gradient with speed shall be so large, stable or unstable, as to interfere with the pilot's ability to control the airplane. Nor shall the magnitude of the control force change from trim, in the speed interval specified in 3.2.9.3.1, be so large as to interfere with the pilot's ability to control the airplane.

C. RATIONALE BEHIND REQUIREMENT

For conditions of relaxed static stability, presumably with a failed FCS and Level 2 and 3 requirements applicable, the pilot will be flying an unstable or near neutrally stable airplane. With these characteristics the pilot must use a different control technique. To describe it roughly, he uses pulses instead of a step or pull and hold. The pilot readily adapts to the different control technique. Large rapid pulse inputs initiate attitude changes and arrest them when the desired change has occurred. Pilots find the presence of large sustained forces objectionable, making it difficult to apply the correct input or "spike". A large F_s/u will produce sustained forces for airspeeds away from equilibrium trim. These are particularly objectionable if they are produced by a large pitching moment gradient with speed (M_u), for then turbulence also upsets the airplane greatly in pitch.

Thus, the force levels in unaccelerated flight and the gradients with airspeed (F_s/u) need to be small, even more so than for stable airplanes. Clearly the trends indicated in Table 1 of 3.2.9.1 do not apply for RSS failure state conditions: Level 2 and 3 requirements should be no higher, probably lower, than the Level 1 requirements of Table 1. Furthermore, the pilot needs an easily usable, rapid trim system to help keep the steady control forces to a minimum.

Since appropriate force and trim characteristics are highly configuration and task dependent, and little data is available upon which to base requirements, the responsibility is placed on the contractor to assure that the control force variation with speed will not interfere with the pilot's ability to control the airplane. Early piloted ground simulations need to be performed in FCS failure states in all conditions where relaxed static stability is present to insure that control force characteristics are adequately low, and trim system characteristics satisfactory. If achieving Levels 2 and 3 are dependent on the trim system, then its reliability under the failure states must be appropriate for the Level.

D. GUIDANCE FOR APPLICATION

Because there is no data upon which to base requirements for force changes with speed in equilibrium flight for relaxed static stability (RSS), piloted ground simulation must be relied upon to investigate and determine satisfactorily low values of F_s/u and F_s changes with airspeed. Chalk's (Ref. 3) equation used in 3.2.9.3.1 (F. Guidance For Application) relating F_s/u to F_s/n is not valid for RSS conditions, but if Chalk's assumptions (good for high static stability) are replaced by assuming $M_w \approx 0$, then the following equation is obtained.

$$\frac{F_s}{u} = + \frac{V}{g}\left(\frac{M_u}{M_q}\right)\left(\frac{F_s}{n}\right)$$

If the c.g. is near the maneuver point so F_s/n is very small, then F_s/u will be very small. Large values of F_s/u will be associated with large values of M_u. Large M_u can occur at transonic speeds, or due to thrust offset especially at low speeds, or any configuration changes automated with speed. These sources of large M_u need to be investigated by simulation, as do any sources of large trim changes occasioned by pilot controlled configuration changes. In evaluating whether steady force levels due to being off trim (either in speed or other source) are satisfactory and do not interfere with pilot control, the control force trim system should be included with due consideration of trim system reliability.

E. DEMONSTRATION OF COMPLIANCE

Demonstration must be by ground simulation, validated by subsequent flight test.

3.2.9.9.2 RSS Pitch Control Forces in Maneuvering Flight

A. REASON FOR REQUIREMENT

The requirements for normal state flying qualities for pitch control forces are unchanged by the presence of relaxed static stability in the control-surface-fixed airplane, so the objective of the first part of this requirement is to explicitly state so and give the applicable paragraphs.

The failure state control force characteristics and requirements are strongly affected by failure to a condition with relaxed static stability. Because of the drastic change, the Level 2 and 3 requirements for stable airplanes are modified appropriately for RSS.

B. RELATED MIL-F-8785C REQUIREMENTS

3.2.2.2, 3.2.2.2.1, 3.2.2.2.2, 3.2.2.3.1, 3.2.2.3.2

C. STATEMENT OF REQUIREMENT

3.2.9.9.2 RSS pitch control forces in maneuvering flight. The requirements for Normal States (augmentation ON, unfailed) of the flight control system are unchanged from those of 3.2.9.1, 3.2.9.2, 3.2.9.3.2, and 3.2.9.4.

For Failure States (augmentation OFF or failed) of the flight control system, the requirements of 3.2.9.1, 3.2.9.2, 3.2.9.3.2, and 3.2.9.4 are modified as follows.

The variation of pitch control force with steady state normal acceleration (3.2.9.1), whether stable or unstable, shall not be so large as to be objectionable or interfere with the pilot's ability to control the aircraft. The numerical requirements or requirements for linearity of pitch control force with steady state normal acceleration of 3.2.9.1 do not apply for RSS with failures (augmentation OFF or failed).

The dynamic requirements of 3.2.9.2 shall be met for frequencies above 1 rad/sec.

The requirements of 3.2.9.3.2 shall be met but the pilot technique shall be that appropriate for the control of aircraft with relaxed static stability. (Note 3.2.9.3.2 is 3.2.9.3 of Ref. 17 and 18).

The requirement of 3.2.9.4 shall be met, except that the gradient of pitch control force per unit of pitch control deflection shall not be so large as to be objectionable or interfere with the pilot's ability to control the aircraft.

D. RECOMMENDATIONS

No numerical values required.

E. RATIONALE FOR REQUIREMENTS

For Normal State flying qualities the FCS augmentation should provide conventional flying qualities, and there is no reason to modify the requirements for

stick force per g (F_S/g) (3.2.9.1)
linearity of F_S vs n (3.2.9.1)
the frequency response, F_S/n ($j\omega$) (3.2.9.2)
change in F_S with rapid speed change (3.2.9.3.2)
force/deflection gradient, (F_S/δ_{ES}) (3.2.9.4)

so the requirement explicitly states that 3.2.9.1, 3.2.9.2, 3.2.9.3.2, and 3.2.9.4 apply for airplanes with control surface fixed RSS with Normal State FCS. This means that the airplane, if near neutrally stable or unstable, will have to be provided with static stability by the stability augmentation functions (feedback) of the FCS, not only for Level 1 within the Operational Flight Envelope but also for Level 2 within the Service Flight Envelope.

However, with the FCS augmentation failed to the point where the relaxed static stability (neutral or unstable) characterizes the response to the cockpit pitch control, there is a drastic change in the maneuver force characteristics. From Appendix B, B.2.3, the gradient of F_S/n is given by the following approximation,

$$\frac{F_s}{n} \simeq \frac{\omega_{n_{csp}}^{\;2}}{M_{F_S}(n/\alpha)} = \frac{\lambda_{csp_1}\lambda_{csp_2}}{M_{F_S}\ (n/\alpha)}$$

where csp refers to the constant-speed short period mode, and λ_{csp_1} and λ_{csp_2} are the real short period roots with speed constant. The constant speed unstable root (λ_{csp_1}) is more stable than the three-degree-of-freedom root (λ_{sp_1}) by a moderate amount (i.e., $\lambda_{csp_1} < \lambda_{sp_1}$). For c.g. at the neutral point and maneuver point, the following conditions occur.

neutral point	$\lambda_{sp_1} = 0$	$F_s/u = 0$
maneuver point	$\lambda_{csp_1} = 0$	$F_s/n = 0$

The above conditions correspond to the stick-fixed case where the feel system provides stick force proportional only to stick position (i.e., no bobweight, downspring, etc). However, if the stick-free roots and characteristics are used instead of the stick-fixed ones, then all three equations above hold even with bob weights, down springs, etc.

The gradient F_s/g is small (positive or negative) or near zero for RSS, but the flying qualities are potentially adequate. Clearly the requirements of 3.2.9.1 on F_s/g are totally inapplicable to RSS conditions. Furthermore, if the average gradient of F_s v.s. g is near zero, as it could well be for RSS, then a very smalll and negligible change in the local gradient could cause very large percentage differences, >> 50%. Again, clearly the requirement for linearity as stated in 3.2.9.1 simply is not applicable to RSS.

No control force or deflection is required to maintain the airplane in equilibrium or steady turns and pullups if the airplane has neutral stability. This is, of course, precisely the basis for the advantage of RSS: no control deflection, no added drag or loss of lift, and maximum performance benefit. With these characteristics, the pilot must use a different control technique (described in 3.2.9.9.1, C, Rationale Behind Requirement) which he can readily do provided the steady force levels are low (F_s/n, F_s/g, etc) and control sensitivity ($M_{\delta_{ES}}$) is adequate.

Fundamentally, the gross control force characteristics are determined by the parametric and frequency response criteria of 3.2.1.3, except for the control/deflection gradient (F_S/δ_{ES}). What remains is to ensure that detailed characteristics such as nonlinearity of force vs. deflection, breakout, hysteresis or nonlinearity of pitching moments with angle of attack or Mach No, or configuration changes do not produce unacceptable conditions. To this intent, the contractor is made responsible in the requirement for ensuring that control force variations with normal acceleration are not too large.

Relaxed static stability affects primarily the response characteristics at low frequencies, below 1 rad/sec, as shown at length in Appendices B and C. For this reason, the dynamic response requirements of 3.2.9.2 on $n/F_S(j\omega)$ are considered applicable, since they apply only above 1 rad/sec.

The control force variations during rapid speed changes are required by 3.2.9.3.2 to be small enough to not cause difficulty, which is as applicable to RSS as it is to stable conditions. However, the final clause requiring normal pilot techniques is modified to allow for the technique appropriate to RSS.

The requirement on control force/deflection gradient, F_S/δ_{ES}, of 3.2.9.4 is accepted with a minimum recommended gradient of 5 lb/in. for center stick and wheel controllers but with an exception noted. The available data for RSS (see Appendix B of this report) indicate a 7 lb/in value to be sufficiently low for center stick controllers. However, in recognition that low force levels are desirable for RSS, and there is not much in the way of data available, none for wheel or sidestick controllers, on F_S/δ_{ES} requirements, a lower level of force/deflection gradient is allowed if a gradient that meets the requirement proves objectionably high. This statement of the requirement recognizes that it would be desirable to have the same gradient for F_S/δ_{ES} whether the FCS is functioning normally or has failed to an RSS condition.

F. GUIDANCE FOR APPLICATION

For failure state conditions of the FCS where relaxed static stability characterizes the airplane's response, the steady state stick force per g will be very low. This is in keeping with the control technique that is required to fly RSS airplanes, pulse control rather than step control. Though quantitative gradient and linearity requirements are not applied to RSS conditions, the force variation with normal acceleration is important, and it should be examined to make sure the control forces are compatible with the pilot's needs. Though sustained normal accelerations cannot be obtained in most ground simulators, ground simulation is still probably the best means for ensuring prior to flight test that the force characteristics are not objectionable.

While lower frequency effects are strongly influenced by RSS, the high frequency control characteristics are not. Above 1 rad/sec the control characteristic with RSS should be much the same as for stable airplanes. The dynamic requirements, couched in the frequency domain, are intended to avoid pilot induced oscillations. Static instability will produce low frequency oscillations, much like limit cycles, at frequencies of 1 rad/sec or less, but the pilots tend not to consider these as pilot-induced oscillations (see Appendix B, B.6.1.4). Also, this type of oscillation will not show up as a resonance in $n/F_S(j\omega)$, or a minimum in $F_S n(j\omega)$. To be avoided are the higher frequency PIO's which can result from resonances in $n/F_S(j\omega)$ and to which the dynamic response requirements are directed.

Because of the control technique the pilot must use (described in 3.2.9.9.1) to handle relaxed static stability, pitch control force levels must be generally low. This is the intent of applying the requirements of 3.2.9.3.2 for control forces during rapid speed changes to RSS conditions. It is also the intent of the modification of 3.2.9.4 for control force/deflection (F_S/δ). If F_S/δ is too high, then the pilot will have trouble making the rapid pulse type inputs needed to handle RSS. High friction and break-out forces, or a sluggish control stick or column, will be found highly objectionable. Ground

based simulation, with special attention paid to fidelity of cockpit control system statics and dynamics, is needed to ensure that these are satisfactory.

G. DEMONSTRATION OF COMPLIANCE

Analytical demonstration of compliance is primarily significant for the control system dynamic requirements (3.2.9.2). Piloted ground simulation should be used to demonstrate that control force characteristics are satisfactory, but flight test verification is mandatory as no ground simulation can adequately simulate the maneuvering environment.

3.2.9.9.3 Pitch Control Force Limits and Trim

A. REASON FOR REQUIREMENT

Under relaxed static stability conditions, low control force levels are desirable to enable the pilot to use the special control technique needed. The purpose of this requirement is to insure that force limits for the various conditions of 3.2.9.7 and its subparagraphs are applied in the context of the special requirements for RSS. Since control force trim (3.2.9.8) can materially assist in reducing sustained forces, there are special requirements with RSS on the performance and reliability of the control force trim system.

B. RELATED MIL-F-8785C REQUIREMENTS

3.2.6.5, 3.2.6.5.1 to 3.2.6.4, 3.2.6.5.6

C. STATEMENT OF REQUIREMENT

3.2.9.9.3 RSS pitch control force limits and trim. The requirements for Normal States (augmentation ON and unfailed) of the flight control system are unchanged from those of 3.2.9.7.1 through 3.2.9.7.7, 3.2.9.8, and 3.2.9.8.1 through 3.2.9.8.3.

For Failure States (augmentation OFF or failed) of the flight control system, the control forces required for take-off, landing, dives, steady sideslips, and control mode changes shall not be so large as to be objectionable or interfere with the pilot's ability to cotrol the aircraft.

In addition, it shall be possible for the pilot to trim the control forces to zero within_______seconds, under all Failure States which involve loss of pitch augmentation that have more than a remote probability of occurrence, without the pilot removing both hands from the pitch controls. This requirement applies to runaway trim.

D. RECOMMENDATIONS

There are insufficient data at present to specify a maximum time for trimming forces to zero for RSS conditions. The time should be as short as possible without being so abrupt that the trim input causes objectionable transients.

E. RATIONALE BEHIND REQUIREMENT

The control force limits specified in 3.2.9.7 and its subparagraphs are in all probability too high, and if realized would interfere with the pilots ability to control the airplane under RSS conditions. The intent of this requirement is to ensure that the contractor will in the design process examine each of the specified conditions, take-off, landing, dives, sideslips, and control mode changes, to ensure that the control forces required are not excessive. For most of these conditions, Level 2 and 3 requirements allow higher forces than Level 1. Where Level 2 or 3 is realized because of failure to RSS conditions, the force limits should probably be lower, not higher, than Level 1 limits. Unfortunately, no quantitative data is available upon which to base specification criteria.

It is thought necessary that the trim system be able to reduce the control forces to zero, including failures and loss of pitch augmentation, for all Levels of flying qualities, in any condition that must be sustained for more than a short time (2 to 5 sec). With any sustained force, release or relaxation by the pilot of the controls could

precipitate divergence. Also, in pulsing the pitch control to initiate or arrest attitude change, the presence of a sustained force makes it difficult for the pilot to judge where the control should be after applying the pulse. Thus the ability to trim out forces to a zero level becomes far more important for RSS conditions than stable ones.

Since rapid trimming of the control forces can materially assist in minimizing deleterious effects of steady or briefly sustained forces, the requirements for trim rate in RSS conditions should be especially high. However, without specific data, the only recourse is to require contractor investigation of trim rates for RSS. Since removal of both hands from the pitch control, under a mistrim condition, could precipitate divergence, one handed operation of the trim system seems mandatory.

F. GUIDANCE FOR APPLICATION

Since no data is available for RSS conditions on the level of control forces or how long they can be sustained before the pilot finds them objectionable, piloted ground simulation should be used early in the design process to assure satisfactory levels.

G. DEMONSTRATION OF COMPLIANCE

Demonstration of compliance must be from piloted simulations, verified by flight test.

3.2.10.4 <u>RSS Pitch Control Displacements</u>

A. REASON FOR REQUIREMENT

Relaxed static stability requires special consideration of pitch control displacement because the pilot or the FCS augmentation system must have sufficient control authority to stabilize the airplane for all disturbances that will be encountered including turbulence. Divergence due to cockpit or surface pitch controls limiting or hitting the stop must be prevented. For this reason it is not enough to require a control

travel margin. The required control authority margin must be provided by the additional travel.

B. RELATED MIL-F-8785C REQUIREMENTS

3.2.3.3.2, 3.2.3.4

C. STATEMENT OF REQUIREMENT

3.2.10.4 <u>RSS pitch control displacements</u> Special requirements on control displacements apply to airplanes with relaxed static stability.

In take-off, the requirement of 3.2.10.1 shall be met with at least the following control power margins_______________.

In all types of landings for which the airplane is designed, the pitch control travel shall be such that the control margins of 3.2.8.6.1 are available to the pilot.

D. RECOMMENDATIONS

Control power margins for takeoff:

$$\Delta M_{c_{max}} = -\ .18 \text{ rad/sec}^2 \qquad \text{nose down}$$
$$= +\ .13 \text{ rad/sec}^2 \qquad \text{nose up}$$

where $\Delta M_{c_{max}}$ is the control power over and above the maximum control used by the pilot during all kinds of takeoffs as defined in 3.2.10.1.

E. RATIONALE BEHIND REQUIREMENT

Control power margin is critical for airplanes with relaxed static stability, especially if the airplane is unstable with pitch control surfaces fixed, as discussed at length under 3.2.8.6.1. Requirements are as critical, if not more so, for the augmented airplane (normal FCS, or back-up FCS) as the unaugmented one. The requirements of 3.2.10 relate to control displacements for takeoff, maneuvering, and gust regulation. Only modifications to these requiements for FCS normal states are

considered here, with failure state requirements covered under 3.2.10.5. The requirements for takeoff need modification, those for maneuvering and gust regulation are acceptable for RSS as stated.

The requirement of 3.2.10.1 is for a specific % of total control travel margin for control usage in normal takeoff, going from rotation through V_{MAX}(TO). The critical conditions for RSS are probably rotation and lift-off where the possibility for over rotation might precipitate divergence due to inadequate control authority, especially in the presence of turbulence. If the control margin of 3.2.8.6.1 were available, over and above the control used in takeoff, then divergence and loss of control in takeoff should be highly unlikely. The margin of 3.2.8.6.1 is based on that required for landing which is a more severe condition than takeoff or waveoff (App. B, C, and Pilot Comments). It should be noted that control margin for landing is the most critical, but total control power might have to be higher in takeoff or waveoff due to thrust or flaps moments which are not reflected in margin requirements. The wording of the takeoff requirement, allowing for insertion of recommended values, recognizes that margin requirements are probably less for takeoff than landing and allows for future reduction from the recommended values which are presently those for landing in severe turbulence.

The requirement for landing is inserted only to ensure that adequate cockpit control displacement is available to make use of the control authority margins required by 3.2.8.6.1 which are stated in terms of angular accelerations.

F. DEMONSTRATION OF COMPLIANCE

Compliance should be initially demonstrated analytically using calculations based on wind tunnel data. Demonstration by piloted simulation is also required, but due to the uncertainties common in the definition of ground effects, flight test demonstration and validation is mandatory.

3.2.10.5 RSS Pitch Control Displacements for Failure States

A. REASON FOR REQUIREMENT

Control displacements as well as forces require special consideration for relaxed static stability (RSS) with FCS augmentation failed. The requirements on sense (direction of deflection) for maneuvering flight are completely different for RSS conditions. Control sensitivity needs special attention for RSS conditions. The intent is to implement these changes in the requirements for control displacements.

B. RELATED MIL-F-8785C REQUIREMENTS

3.2.2.2

C. STATEMENT OF REQUIREMENT

3.2.10.5 RSS pitch control displacements for Failure States. The following modified and special requirements apply to Failure States (pitch augmentation OFF or failed) of the flight control systems.

The requirement of 3.2.10.2 for steady state incremental control deflection in the same sense as initial deflection need not be met, provided the requirements of 3.2.1.3 are met at all steady load factors and pitch rates in turns and pullups for which the aircraft is designed, and provided the control margins of 3.2.8.6 are also met in these turns and pullups.

Control displacements shall not be so large as to be objectionable or interfere with the pilot's ability to control the aircraft in pitch.

Control sensitivity, in terms of pitch angular acceleration per inch of pitch control deflection, shall not be so small that it significantly degrades the pilot's ability to control the aircraft, nor so large that it precipitates pilot induced oscillations. For the approach and landing phase, the control sensitivity shall be within the following limits ____________.

D. RECOMMENDATIONS

Control sensitivity for approach and landing:

$$.25 \leq M_{\delta_{ES}} \leq .55 \quad rad/sec^2/in$$

If control sensitivity for centerstick or wheel controllers is not within these limits, then the contractor must demonstrate in a high fidelity ground simulator that the realized control sensitivity does not cause flying qualities degradation below required Levels in negligible, moderate, and severe turbulence in approach and landing, for both visual and instrument approaches, including flare and touchdown. This demonstration is mandatory for sidestick controllers in all cases.

E. RATIONALE BEHIND REQUIREMENT

For a statically unstable airplane, the change in control position required to maintain a pullup or a turn is small compared to the change required to initiate the maneuver. For c.g. forward of the maneuver point, the initial and final change have the same sense (direction or sign). But for c.g. aft of the maneuver point, the initial and final change are of opposite sense. This latter case, c.g. aft of the maneuver point, will generally be found if the airplane has optimum RSS for maneuvering. Thus the second part of the maneuvering requirement (3.2.10.2) is totally inapplicable to RSS airplanes with augmentation failed to RSS conditions. The requirements for these conditions are covered by the pitch attitude dynamic requirements of 3.2.1.3, the control margin requirements of 3.2.8.6, and the control sensitivity requirements herewith.

The statement of the requirement prohibiting excessive control displacements is needed because of the special pulse technique used by the pilot to control unstable airplanes or ones with low stability, as described in more detail under 3.2.9.9.1.

Control sensitivity strongly affects flying qualities of airplanes in RSS conditions. There is not much data available upon which to base criteria for other than the approach and landing flight phases. For

these flight phases (PA, L) Appendix B of this report provides some data from the ground simulator experiment, correlates these data with flight test data of Smith (Ref. 8) and Wasserman and Mitchel (Ref. 24), to arrive at the recommended range for angular acceleration per inch of stick deflection ($M_{\delta_{ES}}$). The data are extended to wheel controllers, unchanged, partially because the Wasserman and Mitchel data were for a control column and wheel, but mostly because it is felt that, even though control forces need to be generally higher for a wheel (2.15 is the standard used in Ref. 2), the control deflections needed for control of RSS airplanes ought to be the same for a wheel as a center stick. The recommended range is that found to not adversely affect flying qualities, that is, will provide the best flying qualities for unstable or near neutrally stable airplanes. This finding was based on preliminary evaluations performed in the ground simulator tests described in Appendices B and C, plus the observed spread in the Smith (Ref. 8) flight tests.

Responsibility is placed upon the contractor for selecting and demonstrating that control sensitivity is satisfactory in flight phases other than approach and landing. This approach is necessary because there are no data upon which to base quantitative requirements.

F. GUIDANCE FOR APPLICATION

To fly a near neutrally stable or unstable airplane, the pilot must use a different control technique (pulses) instead of the one he uses for stable airplanes (steps, pull and hold). Having adequate control sensitivity is crucial to the pilot's ability to move the cockpit controls appropriately. If control sensitivity is too low, the physical task just becomes too hard.

A crude method for accounting for the effect of control sensitivity on flying qualities through pilot rating is given in 3.2.1.3 (RSS attitude response to pitch controller). The method, a correction for low sensitivity to pilot rating, is applied to both parametric and frequency response criteria of 3.2.1.3. No method has yet been found to develop flying qualities criteria on control sensitivity ($M_{\delta_{ES}}$ or M_{F_S}) based on parameters in the closed-loop frequency response analysis

methods (RSS or Neal-Smith), despite the fact that compensation or pilot gain is a primary parameter in the closure process. The analytical method lumps the data processing parts of pilot gain with the motor part. but while the pilot's data processing gain may be highly adaptable, the motor gain is probably not and must be well matched to the airplane controller characteristics, hence the importance of control sensitivity to flying qualities. For the near neutral or unstable configurations associated with relaxed static stability, the pilot must apply pulse type inputs to control the airplane, which means large amplitudes and high frequencies. If control motions or forces are too high, then physical or motor abilities of the pilot can be exceeded, resulting in a serious downgrading of flying qualities.

For the approach and landing, the criteria and data of 3.2.1.3, reflected in the recommended quantitative criteria of this requirement, will provide guidance in arriving at desirable levels of sensitivity ($M_{\delta_{ES}}$). For other flight phases, piloted ground simulation should be used to develop criteria and arrive at a satisfactory design. Sensitivity which is too low will result in loss of control, either through divergence, or through excessive oscillations at low frequencies, especially where close tracking tasks are involved. Sensitivity which is too high will result in pilot-induced oscillations (PIO's) at high frequencies, just as in statically stable airplanes. The low frequency oscillation associated with RSS, though very properly called PIO's, were not denoted as such by the pilots in the ground simulator experiment of this report (see App. B, C, and Pilot Comments). The oscillations associated with good (Level 2) flying qualities in RSS conditions are more in the nature of a limit cycle, associated with the pilot's ability to resolve airplane motions and his desire to minimize them (how tight does he want to control). Dangerous oscillations of low or high frequency, are ones which grow or increase in amplitude as the pilot increases his gain and tries to damp the motion more tightly. These latter are to be avoided, and are prohibited by this requirement (3.2.10.5) and 3.2.2.

The provision of adequate control sensitivity may be difficult if only mechanical inputs from the cockpit controls to the control surface actuators are provided. Electrical or other inputs to the surface

actuators to increase the gain of pilot inputs should be considered. These, of course, would have to meet flight safety reliability requirements. Where an essential or hard SAS is used to meet minimum flying qualities requirements, Level 3, then an appropriately selected electrical gain would be quite logical, either FBW or parallel to the mechanical path. It should be noted that the control surface stop and the cockpit control stop need not coincide. The surface stop can well be reached before the cockpit control reaches full travel. This was the case for the data shown in Figures 1 of 3.2.8.6.1 for all data points with less than maximum deflection (-15^o and larger), and no pilot rating degradation is indicated until control deflection is limited to $+5^o$ or -3^o.

G. DEMONSTRATION OF COMPLIANCE

Compliance is to be demonstrated by high fidelity ground simulation in all flight conditions where FCS failure can result in relaxed static stability. Validation must be demonstrated in flight test.

H. SUPPORTING DATA

The supporting data comes from the ground simulator experiment of this report (App. B), and the flight test data of Smith (Ref. 8) and Wasserman and Mitchell (Ref. 24). The data are presented, correlated, and discussed in considerable detail in 3.2.1.3 (RSS attitude response to pitch controller). It should be noted that the Wasserman and Mitchell data were for a wheel controller. Sensitivity was quite low and is thought to have degraded flying qualities substantially for their configurations, especially one configuration with anomalous pilot ratings (10 where it should have been 5.5, see Figure 7 of 3.2.1.3).

3.8.1.1 <u>RSS Cross-Axis Coupling in Roll Maneuvers</u>

A. REASON FOR REQUIREMENT

Inertial pitch-roll coupling can be critical for control power and angle of attack limiting, especially at high speeds, for airplanes with

relaxed static stability. Experience with the F-16 airplane, described in 3.2.8.6.3 Lessons Learned, has shown that rapid wing rocks can precipitate divergence and should be considered along with the rolls required in 3.8.1.

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.3

C. STATEMENT OF REQUIREMENT

3.8.1.1 RSS cross-axis coupling in roll maneuvers. The special *requirements of 3.2.8.6.3 apply in addition to those above (3.8.1), but* only for Normal States of the flight control system (pitch augmentation ON, unfailed).

D. RATIONALE BEHIND REQUIREMENT

As described in 3.2.8.6.3 Lessons Learned, the pilot of an F-16 fighter airplane, flying at low altitude and moderately high subsonic speed, performed a series of wing rocks as a signal to another airplane while in a moderate g turn. The airplane pitched up in an out of control divergence and was lost, but the pilot safely ejected. Apparently, pitch-roll coupling caused the angle of attack to successively increase till the stabilator, responding to the augmentation, reached full deflection and could no longer stabilize this relaxed static stability airplane, and it diverged (departed) in pitch. This type rolling maneuver, rocking the wings successively 4 times or more through a moderate bank angle, has not been considered critical. But for the F-16 with its relaxed static stability, it clearly is a critical condition. Accordingly, it is added to the rolling maneuvers which must be examined to ensure there is adequate pitch control power. Since the requirements are specified in 3.2.8.6.3 together with the background information, the requirement for successive rolls is added to the maneuvers of 3.8.1 by reference to 3.2.8.6.3.

Maximum performance rolls should not be a requirement for RSS airplanes with FCS failed, even to moderately relaxed or low levels of stability. Accordingly, the requirements of 3.8.1 are made to apply only to normal states of the FCS (pitch augmentation ON, unfailed). The intent here is to relieve the contractor of designing for maximum performance rolls in an airplane with control-surface-fixed relaxed static stability when the stabilizing augmentation is not functioning properly. No relief is intended for those FCS failures (e.g., one channel of a multiple-redundant computer) which do not affect the RSS augmentation. Under FCS failure states, it is anticipated that the contractor will define reduced levels of performance for the arplane, including roll performance.

E. GUIDANCE IN APPLICATION

Pitch control power, angle of attack limiting by natural aerodynamic means or as an FCS function, and the design of the FCS augmentation system need to be critically examined in maximum performance rolls. It is desirable that no limits be placed on cockpit control motions or maneuvers that the pilot can perform, especially for fighter aircraft or other highly maneuverable aircraft (Class I and IV). However, for RSS airplanes it makes no sense to design for maximum performance rolls under failure states with Level 2 or 3 flying qualities. Thus reasonable restriction on roll performance, ones which will allow breaking off a mission safely, flying home or to an intended destination and landing safely, should be allowed and developed for FCS failure state conditions. However, if an angle of attack limiter is relied upon to avoid loss of control at high angles of attack, then this limiter must continue to perform its function. Also, no single failure (or combination of failures with high probability, e.g., $> 10^{-2}$) should require restricted performance. If the failure occurred during a maximum performance maneuver, the airplane might well be lost before the pilot could recover from the maneuver.

A very pertinent, important consideration is that if an FCS failure to RSS conditions in an extreme maneuver or task might precipitate loss of control, then it could be made highly improbable by redundancy tech-

niques and the use of warning devices. If one or more failures have occurred in a multiple-redundant system, which still leaves the FCS augmentation effective but in some maneuvers or tasks makes the airplane vulnerable to yet another failure, then by warning the pilot of the potential danger, he can abort or avoid the maneuver or task thus eliminating the need to design for it.

F. DEMONSTRATION OF COMPLIANCE

As in 3.8.1

G. LESSONS LEARNED

See 3.8.1 and 3.2.8.6.3

3.8.1.2 <u>RSS Failure State Cross-Axis Coupling in Roll Maneuvers</u>

A. REASON FOR REQUIREMENT

With RSS augmentation failed, the pilot must provide stabilizing pitch control inputs so requirements for pitch-control-fixed rolls are inappropriate. There is no need for maximum performance rolls in a failure state with Level 2 or 3 flying qualities. But roll performance, adequate to the tasks required for these conditions, should be realizable without precipitating pitch divergence or loss of control by the pilot.

B. RELATED MIL-F-8785C REQUIREMENTS

3.3.2.6, 3.3.4, 3.4.3

C. STATEMENT OF REQUIREMENT

3.8.1.2 <u>RSS Failure State cross axis coupling in roll maneuvers.</u> With the pitch augmentation function OFF or failed in the flight control system, there is no requirement for pitch-control-fixed rolls. However, the contractor shall define any bank angle and normal acceleration

restrictions that apply to rolling maneuvers to avoid dangerous or uncontrolled motions, and these shall __(a)__.

At a minimum, with pilot control of pitch and yaw controls, it shall be possible, without causing any dangerous flight condition or precipitating loss of control, to make bank to bank turn reversals from ± __(b)__ to ∓ __(b)__ degrees in Category C flight phases using the roll control input required to meet Category C Level __(c)__ roll performance requirements of 3.5.9.1.

D. RECOMMENDATIONS

(a)

not restrict any maneuver required to perform tasks appropriate to the failure state (Level 2 or 3). Specifically, these restrictions shall not preclude recovery from any maneuver or task where the failure could have occurred. Nor shall these restrictions prevent or interfere with the ability to safely disengage from any mission task where the failure could have occurred, and to safely fly to and land at home base, the terminal destination, or a suitable alternate.

Alternate:

allow roll control inputs of the magnitude required to achieve Level 2 roll performance of 3.5.9.1 (Response to lateral control inputs) in turn reversals with the following bank angles,

Airplane Class	Bank Angle, deg.
I	45
II	45
III	30
IV	60

and also allow safe recovery from any maneuver or task where the failure could occur.

(b)

bank to bank turn reversals

Airplane Class	Bank Angle, Deg
I	45
II	45
III	30
IV	60

(c)

Level 2

E. RATIONALE BEHIND REQUIREMENT

Since pitch-control-fixed rolls are not appropriate for failure states with RSS conditions, and since there is no need for maximum performance rolls under failure state conditions, the requirement for these is eliminated. However, there is a requirement for roll performance which the pilot can successfully cope with in stabilizing an RSS airplane following augmentation failure in order to reach and land safely at home base, the intended mission terminus, or a suitable alternate.

If normal state maximum performance rolls are not required, then limitations or restrictions must be defined which the pilot can readily observe and which will allow safe continuation of the flight to a landing. Restrictions on cockpit control useage are to be avoided, since they are easily exceeded by the pilot in moments of stress, so limitations in bank angle and normal acceleration are allowed on the assumption that these are readily observable by the pilot and are consistent with commonly used normal state restrictions.

It is tacitly assumed that the pilot will not use excessive control inputs in observing the bank angle and normal acceleration restrictions. An alternative assumption could be made that the bank angle restriction should allow for full roll control inputs, but this is felt to be an overly conservative approach.

Alternate requirements are recommended for the first part of the requirement. The first formulation (a) places responsibility for quanti-

tative limits on the contractor, on the assumption that continuation of the mission or an alternate mission is desired after FCS augmentation failure. The second formulation is based on the assumption that safe mission termination and landing is all that is required. For this latter case it is assumed that the most severe maneuver required will be a turn reversal, from a steady turn in one direction to one in the other, and the turns specified are those of MIL-F-8785C, 3.3.2.6.

In addition, safe recovery is required for any maneuvers where the failure could occur. Of concern here are only flight conditions and failures that would result in RSS conditions (low or neutral stability, or instability).

For approach and landing, the task is reasonablly well defined, so quantitative requirements have been formulated, bank angle requirements are those of MIL-F-8785C, 3.3.2.6. Roll performance consistent with Level 2 requirements (3.5.9.1) should be adequate to protect against loss of control.

F. GUIDANCE FOR APPLICATION

For failures which result in RSS conditions (i.e. RSS becomes apparent to the pilot), the only rational way to examine coupling in rolling maneuvers is through piloted ground simulation. Since the pilot has to close a pitch attitude loop to stabilize the airplane, and since he also controls the major forcing function which is the roll control input, no analytical representation is likely to adequately represent this complex situation. Investigation by simulation should determine the adequacy of pitch control power and other FCS characteristics including any angle-of-attack limiter used. Because of the complexity of the roll-coupling problem, even simulation is suspect, and flight test verification is mandatory.

Though analytical results are not likely to do quantitative justice to the roll coupling problem, they probably could serve as a figure of merit to sort out the effects of parameters and to define potentially critical conditions for simulator investigation. Rolls with pitch control fixed, or with pitch controlled by a simple "pilot model", might serve the purpose.

G. DEMONSTRATION OF COMPLIANCE

As in 3.8.1, Cross-Axis Coupling in Rolling Maneuvers.

3.8.4.2.1 <u>RSS Stall Characteristics</u>

A. REASON FOR REQUIREMENT

Stall and high-angle-of-attack characteristics are critical for RSS airplanes. Stability for all angles of attack above stall is desirable, and adequate nose-down control above stall to all attainable angles of attack is mandatory. With static instability at low angles of attack below stall creating the possibility of divergence into stall, an RSS airplane must have exceptionally desirable control and recovery characteristics at stall and above so that the pilot or the FCS can prevent divergence into an unrecoverable stalled condition.

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.2.1.2

C. STATEMENT OF REQUIREMENT

3.8.4.2.1 <u>RSS stall characteristics</u>. It is desired that the pitching moments break stable at the stall, and remain stable above the stall. However, instability and pitch-up are permitted provided the requirements of 3.2.8.6.4 are met.

D. RATIONALE BEHIND REQUIREMENT

The requirements of 3.8.4.2 are not sufficiently stringent for an airplane with relaxed static stability. The more stringent and quantitative requirements of 3.2.8.6.4 need to be added to those of 3.8.4.2, especially the control power requirements and what amounts to the prohibition of a stable deep stall either by inherent aerodynamics characteristics or through an angle of attack limiter with flight safety effect-

iveness and reliability. Further details are covered extensively under 3.2.8.6.4.

E. GUIDANCE FOR APPLICATION

As in 3.2.8.6.4

F. DEMONSTRATION OF COMPLIANCE

As in 3.8.4 and 3.2.8.6.4

3.8.4.3.1 <u>RSS Stall Prevention and Recovery</u>

A. REASON FOR REQUIREMENT

Prevention and recovery from stalls must be assured for RSS airplanes with or without FCS augmentation. The only exception is failure of an essential FCS function (3.1.11.2 and 3.1.11.2.2) for which loss of the aircraft is allowed. The intent of the requirement is to explicitly state that the requirements of 3.8.4.3 apply both with or without normal FCS augmentation.

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.2.1.3

C. STATEMENT OF REQUIREMENT

3.8.4.3.1 <u>RSS stall prevention and recovery.</u> The requirements of 3.8.4.3 apply to aircraft with relaxed static stability, for both Normal and Failure States.

3.8.5.3 RSS Departures and Spins

A. REASON FOR REQUIREMENT

Airplanes with relaxed static stability must have departure resistance equal to or better than that required of stable airplanes, and must be as readily recoverable, if not more so, from post-stall gyrations and spins. These characteristics must hold in both normal and failure states of the FCS augmentation, essential FCS functions excepted (see 3.1.11.2 and 3.1.11.2.2). However, if an angle-of-attack limiter of sufficient reliability will prevent departures from controlled flight and hence post-stall gyrations and spins, then there seems to be no need to meet requirements concerned with departures or spins.

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.2.2, 3.4.2.2.1, 3.4.2.2.2

C. STATEMENT OF REQUIREMENT

3.8.5.3 RSS departures and spins. The requirements of 3.8.5.1 and 3.8.5.2 apply to aircraft with relaxed static stability, both for Normal States and Failure States (pitch augmentation OFF or failed) of the flight control system, except for aircraft which meet the requirement of 3.2.8.6.4 by virtue of angle of attack limiting. In this latter case the requirements of 3.8.5.1 and 3.8.5.2 need not be met, provided departures from controlled flight are shown to be extremely remote (probability, $\leq$ _____).

D. RECOMMENDATIONS

The allowable probability of encountering worse than Level 3 flying qualities of 3.1.11.2.2, Table 1.

E. RATIONALE BEHIND REQUIREMENT

Airplanes with relaxed static stability could be more prone to departure, post-stall gyrations, and spins than stable airplanes because of the instability at low angles of attack. To avoid problems at high angles of attack, exceptional requirements on control and stability above stall are levied by 3.2.8.6.4. Since these requirements may be difficult or impractical to meet with natural aerodynamic means, the alternate approach of automatic angle-of-attack limiting is allowed, provided control and reliability requirements can be met. The angle-of-attack limiter, presumably an FCS function, becomes part of the essential augmentation system (3.1.11.2) with flight safety reliability required (3.1.11.2.2).

Recovery from stalls, departures, post-stall gyrations and spins must be handled differently for RSS airplanes. Since the airplane will in all probability be unstable in recovery without augmentation, automatic disengagement of the augmentation system in stalls or departure conditions is not permissible (3.8.5). Any automatic suspension of augmentation functions during stall or departure, must be followed by automatic re-instatement during recovery. For the unaugmented airplane or with essential SAS, recovery will be to a less than Level 1 airplane. Since Level 3 flying qualities in recovery must be assured, and since conditions in recovery could be worse than most others, these conditions could be the critical ones for FCS failures.

The presumption is that if the control requirements of 3.2.8.6.4 are met, together with their implications on stability at high angles of attack, then characteristics in pitch will be satisfactory for all high-angle-of-attack conditions. Then application of the normal requirements for the other axes as defined in 3.8.5.1 and 3.8.5.2 should result in satisfactory stall or departure and recovery characteristics, provided low-angle-of-attack characteristics in recovery are also satisfactory.

The major considerations not covered by the foregoing are the use of an angle of attack limiter and the possibility of departure from controlled flight for angles of attack less than stall if the requirements of 3.8.5.1 and 3.8.5.2 are not applied. This requirement

(3.8.5.3) allows disregard of the departure and spin recovery requirements if departures and flight at excessive angles of attack are prevented with sufficient assurance. The requirement as stated allows inherent aerodynamic means to be used for departure prevention, but the implication is that the angle of attack limiter function will be broadened to provide a complete departure prevention system. To disregard 3.8.5.1 and 3.8.5.2, the system must have better than flight safety reliability.

F. GUIDANCE FOR APPLICATION

Provision of a departure prevention system is highly desirable, even if it does not meet flight safety standards and the requirements of 3.8.5.1 and 3.8.5.2 for departure resistance and recovery from post-stall gyrations and spins must still be applied. A departure prevention system, if properly designed, will allow the pilot complete freedom to maneuver the airplane in "heads-up" flight (with no reference to cockpit instruments) and will enhance maneuverability, especially in air combat (Ref. 35, 45, and 42). It can allow an expanded usable maneuver envelope (Ref. 40).

Careful consideration must be given to failure states so that relaxed static stability will not precipitate loss of control. Careful consideration must also be given to roll coupling effects, since these can be critical as they were for the YF-16 (Ref. 45). Even if the design is predicated upon a complete departure prevention system, with adequate reliability incorporated for all flight safety critical functions, there is still the possibility of departure and subsequent post-stall gyrations or spins because of the complexity and uncertainties involved. Accordingly, gyration and spin recovery should be investigated by analysis and model tests at least until flight test proves departures are fully prevented. For fighter aircraft, consideration should be given to vertical flight to very low airspeeds, even to tail slides. Prevention may be necessary, by including automatic thrust control or other means, or by restricting allowable airspeeds with appropriate warning provided to the pilot so he can still fly "heads up".

G. DEMONSTRATION OF COMPLIANCE

As in 3.8.5, 3.8.5.1, and 3.8.5.2

H. LESSONS LEARNED

YF-16 and F-16 experience provide considerable information on potential problems and hazards (Ref. 41, 45, and 42). For the YF-16, a primary deficiency was its susceptibility to roll coupling (Ref. 41 and 45) which was not adequately cured in the F-16 (3.2.8.6.3, Lessons Learned).

3.8.6 Control Coupling for Failures with RSS

A. REASON FOR REQUIREMENT

An insidious form of coupling of roll control into pitch was encountered in the simulator experiment of this report. Because of relaxed static stability, if roll inputs cause pitch inputs through coupling in the flight control system, then this control coupling can have serious consequences, even loss of control. Roll inputs into pitch must be adequately minimized.

B. RELATED MIL-F-8785C REQUIREMENTS

3.4.4

C. STATEMENT OF REQUIREMENT

3.8.6 Control Coupling for failures with RSS. For failures of the normal pitch augmentation system (augmentation OFF or failed) for airplanes with relaxed static longitudinal stability, roll control inputs commanded by the pilot or from the augmentation system shall not cause objectionable pitching motions for maneuvers appropriate to the failed condition. Specifically, this applies to bank to bank turns from _______ to ______ degrees of bank angle for Category C flight phases.

D. RECOMMENDATIONS

Bank angles for bank to bank turns in Category C flight phases.

Airplane Class	Bank Angles, Deg
I	45
II	45
III	30
IV	60

E. RATIONALE BEHIND REQUIREMENT

The simulator experiment of this report (App. B) encountered serious degradation in flying qualities due to an insidious form of coupling of roll control inputs into the pitch control (see B.5.1 and B.5.2). In one case, the pilot rating went from 5.5 to a 10, or from Level 2 to worse than Level 3. The basis for the problem was that the simulation airplane had a rolling tail. As on many recent fighter aircraft, left and right horizontal tails were deflected symmetrically for pitch and antisymmetrically for roll inputs. With pitch control input at maximum, the horizontals were against the stops, and a roll input caused one tail to deflect but not the other. This caused an effective pitch input cue to roll, as the average left and right deflection was reduced and changed. The effect was most pronounced in recovering to wings level from a left or right bank following a sidestep maneuver to line up with the runway during visual short final. The pilots interpreted the response as a severe "gust", as they saw no other reason for the severe pitch up and "ballooning". The solution to the problem was to rearrange the control system (inputs, servos, actuators) so that the roll input could be limited, to prevent symmetrical deflections from roll control.

The above problem was encountered only with pitch augmentation failed. The source of the problem was the static instability, combined with the pulse technique used by the pilots which necessitated large control inputs. The pilot most susceptable to the problem in the simulation was the most agressive one, who used the largest and most abrupt or rapid inputs.

Though the problem described above was encountered in the control system. the same result would be expected if the roll control surface created large pitching moments as spoilers might. The problem occurred in approach and landing, where pitch control surface deflections were largest. Thus the emphasis in the requirement is on Category C flight phases. The quantitative requirements are consistent with those of 3.8.1.2.

For the augmented airplane, it is not so likely that the same phenomena would be encountered since the augmentation would be approximately linear. It was not encountered for the augumented airplane in the investigation of this report.

F. GUIDANCE FOR APPLICATION

Any coupling of roll control into pitch, either in the FCS or through aerodynamic means, should be minimized. Such coupling should be examined critically, especially for FCS augmentation failures at low speed. Examination would be through piloted simulation.

G. DEMONSTRATION OF COMPLIANCE

Compliance should be demonstrated through ground simulation, verified by flight test.

SECTION V
ADDITIONAL RESEARCH REQUIRED

The proposed requirements for relaxed static stability (RSS) in Section 3 and 4 have been formulated based on the meager amount of data that exists, augmented substantially by the ground simulator investigation described in Appendix B of this report. The need for this simulation program was critical because most of the existing data were generated looking only at the effects of aft shifts of the c.g., and reporting failed to provide adequate information on the airplane characteristics. Neither could the independent influence of the various airplane parameters be isolated, nor could the data be correlated between the various investigations. Notable exceptions to these deficiencies were the work of Wasserman and Mitchell (Ref. 24) and Smith (Ref. 8), both approach and landing flight test programs. All data are of some value, but the need is for data from well conceived experiments, reported with adequate documentation to allow comparisons between experiments.

Ground simulator data are valuable, because the characteristics in the experiment can be much more carefully controlled than in flight test. Ultimately, flight test data must be obtained to validate ground simulator results and to provide data where the simulator fails to adequately simulate the airplane and its physical environment. Perhaps foremost of the inadequacies is the ability to simulate sustained accelerations, which appear to be important in the pilot's ability to fly an unstable airplane, especially in air combat type maneuvers. Another is the limited ability to simulate the total flight environment, the motion cues, the outside world, and the psychological effect of knowing that "the g's are really bending the wings". Still a third is the inadequacy of simulating complex situations with significant uncertainties and nonlinearities, extreme maneuvers as in high-rate rolls, stalls, departures, post-stall gyrations, and spins.

Research is most needed to provide more data on which to base requirements, especially in other than approach and landing. But, analysis methods also need more work, especially to further develop the closed-loop frequency response technique pioneered by Neal and Smith (Ref. 7). More specific considerations follow.

Unaugmented or Failure State (3.2.1, 3.2.8, 3.2.9)

The approach and landing simulation data of Appendix B of this report need to be expanded for the unaugmented or failure state:

a) Larger λ_{sp_1} (smaller T_2)

b) Variations of Z_{θ_2} for various combinations of λ_{sp_1} and λ_{sp_2}

c) Effect of $M_{\delta_{ES}}$ and F_S/δ_{ES} for various combinations of λ_{sp_1}, λ_{sp_2} and Z_{θ_2}.

d) Extend results to other flight conditions

Air combat maneuvering

Low altitude, high speed terrain following

Dives - maximum speed, g's, dynamic pressure

Cruise - long flight times, 10 min to hour or more

e) Phugoid characteristics - poles in right-half plane, see Figures B-2, B-3.

f) Controller force/deflection characteristics

$M_{\delta_{ES}}$, M_{F_S}, F_S/δ_{ES}, F_S/n in various flight conditions

Wheel controller

Side stick controller

Steady forces - sustained g, out of trim

Control Power (3.2.8, 3.8)

The control power requirements need to be much better defined, at both low and high angles of attack, for augmented and unaugmented (or FCS Failure State) airplanes, for both control margin and rate.

Flight condition - airspeed, dynamic pressure

Stall - accelerated stalls

Departure - P.S.G's and spins, prevention

Roll coupling - rolls at high g's, augmented and unaugmented

Analysis Methods

The closed-loop frequency response method of Neal and Smith (Ref. 7) appears to offer significant advantages in providing the basis for

criteria for relaxed static stability as well as higher order systems. Further development and application in the following areas is needed.

Improved pilot model - add lag with RSS lead
Apply to other existing data - Ref. 24, etc.
Simulation - Feel system, actuator variations to develop BW = 3 rad/sec RSS criteria

Special Problem

The effect of Z_{θ_2} was found to be extremely significant as shown by data in Appendix B. This may be due to the coupling into angle of attack or heave response ($n/\alpha \simeq -VZ_{\theta_2}/g$), or due to the lead produced by small Z_{θ_2} in the θ/F_s transfer function, or both. A ground simulation program should investigate these effects, followed by flight test investigation since normal acceleration response can not be adequately represented other than in flight. Knowledge of why Z_{θ_2} so strongly affects flying qualities could be valuable for FCS design.

SECTION VI
CONCLUSIONS

1. The long held criterion for the amount of static instability in pitch allowable, based on time-to-double amplitude (T_2), stated in MIL-F-8785C as $T_2 > 6$ seconds, is essentially invalid. Other parameters in the θ/F_s transfer function are found equally, if not more, important.

2. The result of fixed-base ground simulation of approach and landing show that criteria for relaxed static stability can be based on four primary parameters, the value of the short period roots (λ_{sp_1} and λ_{sp_2}, the small positive root and the large negative root), the large zero in the θ/F_s transfer function (Z_{θ_2}), and control sensitivity ($M_{\delta_{ES}}$ or M_{F_S}). For the criteria to hold, the phugoid roots must be small. An alternate frequency domain criterion, based on the closed-loop characteristics of θ/F_s developed by Neal and Smith (Ref. 7), can satisfactorily handle all the above parameters with the exception of control sensitivity. In addition, this frequency response approach looks promising as a criterion able to account for phugoid as well as control system and higher-order characteristics (i.e., anything that affects the pitch attitude response for $\omega > .1$ rad/sec).

3. Pitch control margin is a critical parameter in the design of airplanes with relaxed static stability in pitch, for augmented as well as unaugmented airplanes. Existing data for approach and landing, and level flight unaccelerated stalls, seem to correlate well, and give a reasonably sound basis for criteria. For accelerated stalls, extreme maneuvers as in maximum performance rolls and especially at higher g, departures, post-stall gyrations, and spins, adequate data are not available to formulate sound criteria. This applies also to departure prevention.

4. Pitch control rate is even more critical than control margin, and fairly high rates for control surface deflection are required, on the order of 1/3 of a second for full deflection from neutral.

5. The theory and approach developed in Appendix B of this report, and reflected in the proposed requirements of 3.2.1.3, provide a new and sound basis for developing adequate flying qualities criteria for airplanes with relaxed static stability in pitch.

6. Airplanes can be flown with far more static instability than has been previously recognized, or they can be very bad even when stable, depending on various other parameters. For example, an airplane with time-to-double of 2 seconds can have good flying qualities (pilot rating of 3), while an airplane with time-to-double of 6 seconds can be unflyable (pilot rating of 10). Examples of each can be found in the ground simulator data of Appendix E.

7. More data are needed on stability levels, control margin and rate, and control force and deflection. The need is especially for data other than in approach and landing.

SECTION VII
RECOMMENDATIONS

1. Ground simulator investigations should be performed to extend the results obtained in Appendix B of this report, to larger values and more combinations of parameters for approach and landing, and to other flight conditions, as detailed further in Section 5.

2. The frequency domain approach to criteria for relaxed static stability should be further developed as it appears to offer far more promise than other approaches (parametric, or equivalent system). The following specifics are recommended.

   a) Improve pilot model by adding lag to go with lead added for RSS.

   b) Apply technique to additional existing data (Ref. B-27 and others).

   c) Develop BW = 3 rad/sec RSS criteria by applying to RSS cases with degraded actuators and feel systems. Generate simulator data for that purpose.

3. Investigate effect of large zero in θ/F_S transfer function ($Z_{\theta_2} = -1/T_{\theta_2}$), to separate n/α effect from lead effect, for conditions of relaxed static stability. Use ground simulation, followed by in-flight simulation.

4. The data in Appendix A on accidents show the need for a flight path control requirement for engine-out for multi-engine aircraft on takeoff, especially from carriers. The requirement needs to specify quantitative flight path control, on loss of an engine, with no configuration changes permitted (i.e., pilot moving only stick or wheel, rudder pedals, and thrust controls). Data needs to be collected for acceptable flight path control response, from existing aircraft if possible or from simulation, and an appropriate criterion formulated.

5. Radford and Smith (Ref. 46) investigated and found significant the variation with bandwidth (BW) of the criterion parameters in the Neal-Smith closed-loop frequency domain approach. Results of the simulator investigation described in Appendix B suggest that the pilot in controlling the airplane does not use constant gain, roughly equivalent to constant BW; rather, he varies his gain and also possibly lead as a function of the momentary situation. This suggests that a continuous variation with bandwidth of the criterion parameters (pilot lead, resonant amplitude, possibly others) would provide a better basis for criteria and requirements than the current fixed-bandwidth approach. It is recommended that work be initiated with this objective, not just for RSS criteria, but for the general case.

6. Investigation of characteristics for RSS airplanes need to be conducted by ground simulation and in flight. Two specific areas are recommended in addition to the one recommended in Item 3:

   a) Control force/deflection gradients (F_S/δ_{ES}, F_S/n, etc) and sustained force levels (steady turns, out of trim, failure conditions).
   b) Control power and rate required in level-flight and accelerated stalls. Limits should be varied for both control surface position and rate.

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